WESTINGHOUSE
Engineer
May, 1944

# *The Condenser Bushing—*

## —A SIMPLE ELECTRICAL PRINCIPLE AT WORK

High voltage is like a fractious horse. Electric power can be led across miles of open country without serious difficulty. But bring it through the narrow opening in the steel tank of a circuit breaker or transformer and you have a stubborn problem to deal with. Back about 1905–1910, when transmission voltages were beginning to creep above 100 000, the matter of insulation at the entrance of transformer and breaker tanks threatened to set the limit of voltage at which electric power could be transmitted.

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Many approaches to the problem of high-voltage terminal insulation have been tried. A most curious one was an early bushing made of Portland cement within which was located a Micarta-covered brass tube. In fact, the first 100 000-volt transformers manufactured for power purposes (1907) were equipped with this type of terminal. They continued in uninterrupted service until some time after 1913.*

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The task of providing insulation at the entrance to steel tanks presents a difficulty that often arises in engineering. Under many circumstances a structure cannot be made stronger by making it larger. This occurs with electrical structures as well as mechanical ones. Doubling the thickness of an insulation does not double its strength as a dielectric by any means. In fact, making a thick block of insulation still thicker may result in almost no greater ability to withstand stress. Voltage has the habit of distributing itself unevenly across insulation. It piles up at the boundaries. A plot of voltage stress per unit thickness of insulation, instead of being a straight line, looks more like a loosely hung clothesline.

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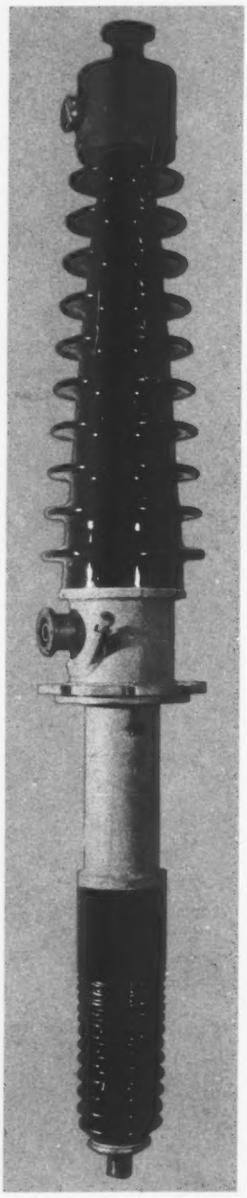
In 1907 some 88 000-volt equipments (requiring test voltages of 176 000 volts) were being built for an electric railway company in Brazil, and serious difficulty was being met in providing terminals that would withstand the test voltages. Mr. A. B. Reynders, then assistant to manager of engineering of the Westinghouse Electric & Mfg. Company, chanced to see some notes of European experiments with condenser-type insulation to obtain a better distribution of voltage stress. Under Reynders' direction, a small-scale bushing was made and tested. It proved so successful that terminals were made of layers of paper and tinfoil. Each terminal was only six inches in diameter and 96 inches long (the limit of paper then available), yet it readily met the 176-kv test. In this manner the high-voltage condenser bushing was born. This condenser principle is now the senior high-voltage insulation principle, having a longer period of service than any other type of bushing. Although the methods used in manufacturing this type of bushing have been improved many times, the basic principle has not changed. Actually, the appearance has changed but little. The size for a given voltage class has not been altered appreciably, which has not been necessary anyway because of the inherently small size of the condenser-type bushing. These bushings have encountered no voltage "ceiling," and none is likely.



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The condenser bushing is based on a single, simple principle of electricity. Alternating-current voltage across condensers in series will divide among them in proportion to their individual capacitances. If the capacitances of all the condensers are equal, then the voltages across each are equal. The insulation of a bushing, therefore, is made of many condensers of equal capacitance in series instead of a single condenser as is the case when the entire voltage is carried across one body of insulating material. In this manner the actual voltage per unit of thickness remains constant.

• • •

The condensers in series in the high-voltage bushing are made of paper and metal foil. Several layers of paper, which is the dielectric, are tightly wound on the copper conductor to be insulated. Then a layer of foil is placed around the paper, to act as the electrode of the condenser. Next, more layers of paper are wound on, followed by another electrode layer (metal foil), and so on until the desired number of condensers is obtained.

• • •

The matter of obtaining equal capacitances from the condensers must be attended to. Capacitance of a condenser is proportional to electrode area and inversely proportional to thickness of dielectric. Because the electrode area of the outer layers is greater than the area of the layers nearer the conductor core, the outer condensers will have too much capacitance unless something is done about it. Either the number of layers of paper (i.e., thickness of dielectric) or the foil area must be varied as the diameter increases. The foil area is controlled after the condensers are wound by machining the winding in steps so that the product of length times circumference for each layer of foil is the same for all electrodes, thus keeping the square inches of area for each electrode uniform. Fortunately, this also provides uniform distribution over the creepage surface from the flange to the bottom of the bushing as well as from the conductor to the outside. With the condensers of equal capacitance the curve of voltage stress per unit thickness is no longer like a sagging clothesline, but is like a line with props at such frequent intervals that the sag is almost imperceptible, thereby efficiently working all of the insulation at a uniform stress.

*"The Condenser Terminal" by C. L. Fortescue, *The Electric Journal*, August, 1913.

WESTINGHOUSE

# Engineer

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VOLUME FOUR MAY, 1944 NUMBER THREE

*The cover:* High-voltage bushings have become as symbolic of electric power as the transmission tower. These bushings now have an improved insulation, such as used in modern transformers.

How's *your* electronics? You need have no doubt about the coming technical generation being perfectly at home with electrons and megacycles. Within a few weeks after college-laboratory electronic equipments were made available, 81 engineering schools had purchased complete sets. Each set includes a representative group of industrial electronic tubes, ignitron rectifier, electronic timer, phototube, automatic synchronizer, voltage and speed regulators, x-ray, and other electronic equipment.

A turbine designer, asked about a large non-condensing machine recently placed in service by an industrial company, shook his head sadly and said, "We just can't win! The machine is *too* efficient. Because the efficiency is considerably better than the guarantee, the temperature of the exhaust steam is too low for use in plant process work." Efficiency-decreasing measures have been taken.

Evidence that engineering is a young science is the fact that there is more—much more—to be learned about every phase of it. Even an old subject like heat transfer. To explore this subject further, a five-year training and research program has been established at Purdue University and sponsored by Westinghouse. The work will be under the direction of Dr. George A. Hawkins, of the Purdue faculty, now Westinghouse Research Professor in Heat Transfer.

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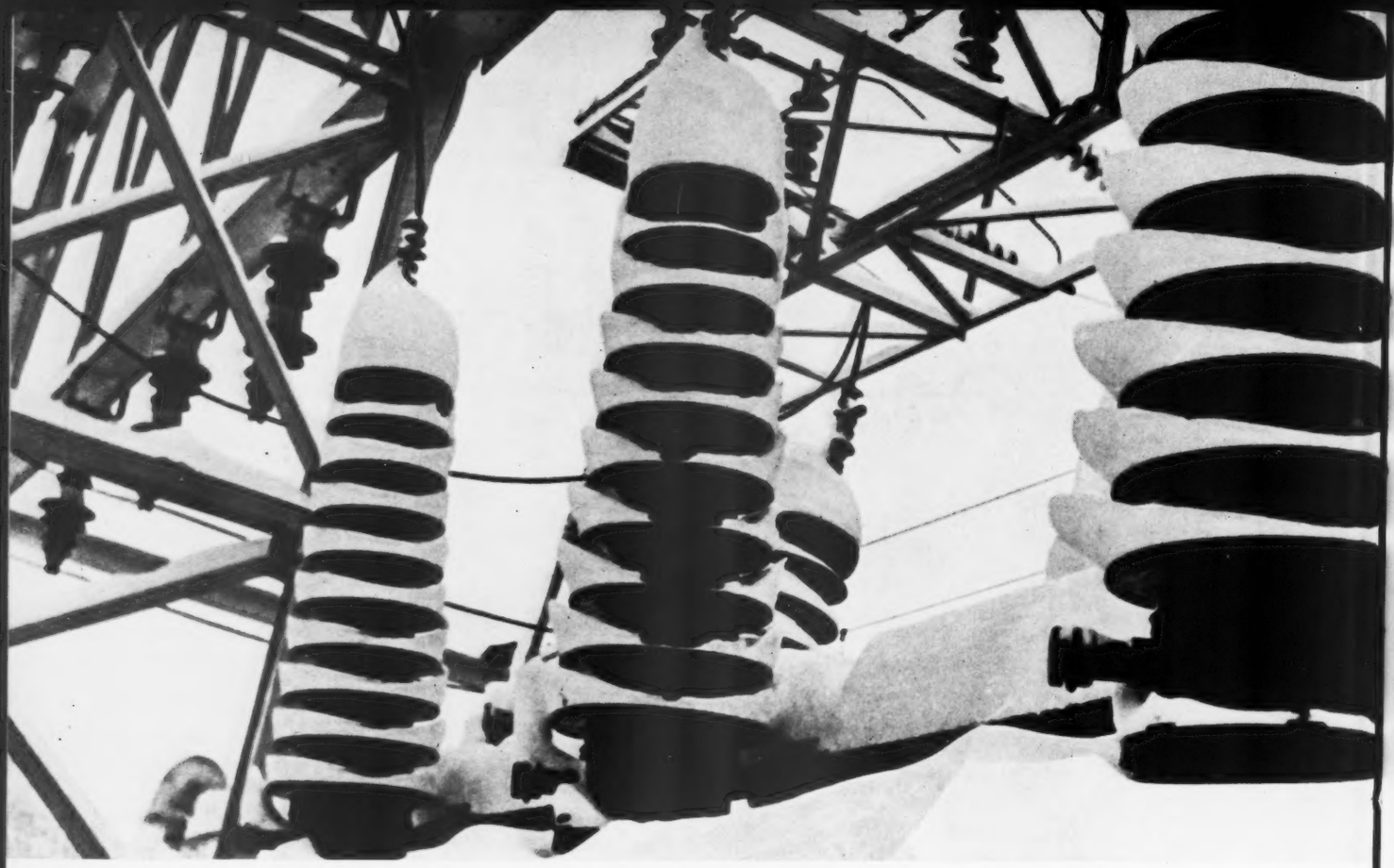

# Improved Condenser-Bushing Insulation

*Ideas that lead to basic improvement in one kind of electrical apparatus soon spread to other equipments. The condenser bushing—the type with most years of service—is the recipient of three ideas proved excellent by transformer experience. It uses paper insulation that is vacuum treated, oil impregnated, and hermetically sealed.*


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ALL BASIC forms of electrical apparatus are continually undergoing detail improvement. Then, at rather rare intervals, a complete, major redesign appears. The need for this infrequent but major overhauling of design results from new and more severe service requirements, the availability of new or improved materials, better manufacturing processes, more revealing test procedures, etc. The high-voltage condenser bushing used with circuit breakers and transformers has just experienced one of these major re-creations. The basic principle of the condenser bushing remains unchanged. The purpose was to obtain more electrical strength, greater thermal stability, and a far higher degree of service reliability even for today's increased service requirements.

In high-voltage transmission and distribution, high-voltage bushings must perform with unvarying reliability under all weather and circuit conditions. Reliability is not a temporary requirement. The bushing must be as capable of withstanding abnormal voltages and currents after it has been in service many years as when it was first installed, with the minimum of service or attention.

This matter of reliability is particularly vital with high-voltage bushings. Even the normal low percentage failure rate acceptable for most electrical apparatus cannot be tolerated with bushings, because of the consequences that result from a bushing failure. The bushings are connected to the high-voltage side of equipment that is expensive and often unsupported by spares. They are exposed to lightning strokes and mechanical shocks. Little or no servicing of them can be done in place, and to remove them is difficult and expensive because facilities for handling objects of their weight and bulk are not generally available at the installation location. Occasions when bushings can be removed occur infrequently; the time for such servicing is brief.

Bushings are subjected to wide temperature differences. On a summer day one side of the exposed portion may be accepting heat from the sun. On a winter day the outer porcelain may be exposed to high winds and minus 40 degrees F temperature. In either condition the lower end of the bushing may be in the relatively hot oil of a transformer or the cooler oil of a circuit breaker. Furthermore, the temperatures at which apparatus is allowed to operate have been increased in recent years. All of these factors impose a large thermal problem on the high-voltage bushings.

New facts have come to bear on bushings.

The transformers and breakers with which they are used have become progressively smaller. It is essential that bushings be small so that tanks can be designed primarily to house the apparatus and not as a support for relatively large and heavy high-voltage bushings. Small diameter for a given rating is additionally important because it reduces the diameter of through-type current transformers, which permits better performance to be obtained. Bushings built on the condenser principle are smaller than any other type because the insulation is stressed uniformly.

The advent of power-factor testing of insulation has pointed to the need for improvement in high-voltage bushings. It has emphasized a characteristic of insulation temperature instability that must be carefully guarded against in design. At normal ambient temperatures the power factor (i.e., watts loss or heat generated in insulation) of the insulation may be relatively low but it will rise as temperature is increased. If this rate of rise of power factor for a given insulation should be fairly high, a "runaway" condition may be encountered. That is, as the temperature rises the internal losses increase, which increases the temperature, and so on until failure ensues.

The work done in high-voltage laboratories—such as the three-million volt laboratories at East Pittsburgh and Sharon, Pennsylvania—has provided new evidence of the magnitude of the problem of bushing insulation. As a result of extensive studies with both steady-state and transient-voltage phenomena, the desirability of bushings with increased impulse strengths has become manifest. This is particularly true for surges with steep wave fronts, because surges resulting from near-by lightning strokes may be imposed on the bushings of transformers and breakers.

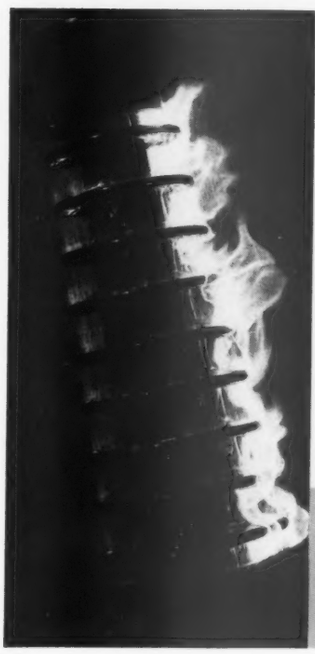
To fulfill these requirements necessitated more than detail changes in condenser-bushing construction. A bushing, known as type O, incorporating major construction changes, has been developed. The design for this new bushing borrows heavily from modern transformer practice. In fact, the new bushing insulation is built much like transformer insulation that has proved so successful. Three basic principles of construction underlie that success. One is the use of organic insulation that, after assembly, is thoroughly vacuum treated to remove all moisture and gases. This includes the gases that are trapped between structures and those actually within the insulation itself. A second basic requirement is to oil impregnate the insulation while in the gas-free condition, with degassed hot oil under pressure. This insures complete filling of all voids and interstices with oil. Finally, the bushing is sealed hermetically so that this moisture-and gas-free condition is permanently retained.

The new condenser bushing consists, as always, of layers of high-grade paper, wound under tension on the copper conductor, which is a copper tube or stud. In accordance with well-known condenser-bushing principles, sheets of metal foil are inserted at intervals. Except for an adhesive to bind the first turn of paper to the conductor, the paper is wound dry, with no binder between layers, as in the best modern transformer practice. There is, likewise, no subsequent varnish treatment of the insulator surface to interfere with oil penetration. After the winding has been made in this manner—usual except for the absence of the shellac between layers and the final varnishing—and is machined to proper dimensions, the structure is placed in its porcelain housing. In the new bushing, the condenser is completely enclosed by upper and lower porcelains connected at midsection by a steel sleeve. Thus the condenser projecting down into the tank is encased in porcelain as is the upper end. The assembled bushing is now heated for some time while a high vacuum is maintained within the porcelain housing.

TABLE I—DIELECTRIC LOSSES IN TYPE O CONDENSER BUSHINGS

| Voltage Rating of Bushing | Capacitance $\mu\mu f$ | Watts Loss in Condenser | |
|---|---|---|---|
| | | 25°C, 0.006 PF | 85°C, 0.01 PF |
| 115 | 412 | 4 | 7 |
| 138 | 425 | 6 | 10 |
| 161 | 464 | 9 | 15 |
| 196 | 537 | 16 | 26 |
| 230 | 615 | 25 | 41 |

In this process the gases within the paper are drawn off. With the condenser still held in the strong vacuum, the bushing is filled with oil that has been thoroughly dried and freed of gas. Oil is applied hot and under pressure until the paper is completely oil impregnated. Dry nitrogen at slight pressure is introduced into the space at the top of the bushing to exclude oxygen and to maintain positive pressure as the oil absorbs some of the trapped gas. The result is an oil-impregnated insulated structure surrounded by oil and hermetically sealed within porcelain.

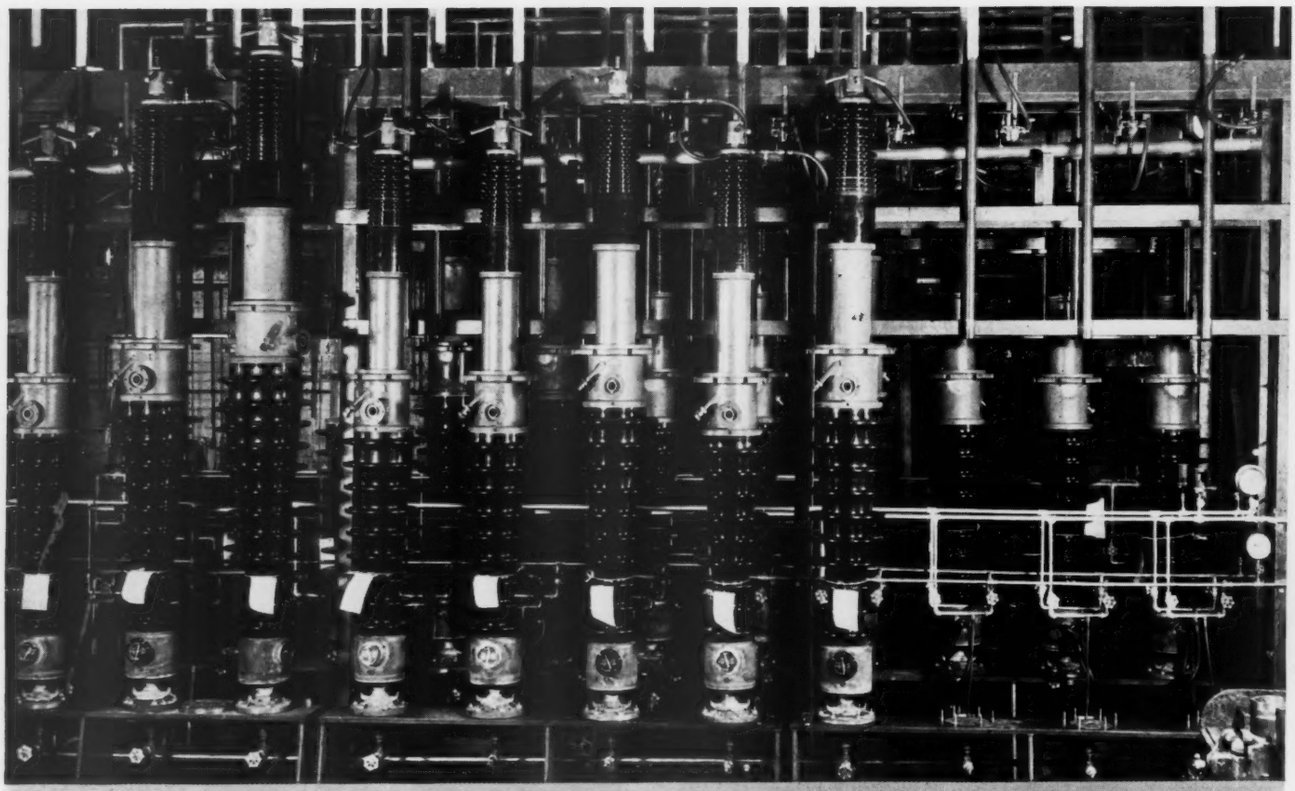


*Representative high-voltage bushings are purposely flashed over to disclose their behavior on surges from "close-in" lightning strokes.*

The metal-to-porcelain seals are made by sealing gaskets of cork-neoprene composition, kept under continuous but controlled pressure. The pressure is provided by heavy coil springs in the cap. The control of pressure on the sealing gaskets is obtained by installing hard stop gaskets in parallel with the sealing gaskets, thus limiting deformation of the sealing materials. All joints, except those between porcelain and metal, and the sampling valve, which is a high-pressure, metal-to-metal seal are either soldered or brazed. This construction has proved effective in eliminating gas and oil leaks. Differential expansion between porcelain and copper is absorbed by flexibility built into the cap. All gaskets are located below the oil level so that any leakage at the gasketed joints can be readily detected by the outward flow of oil.

In this bushing the mechanical and electrical functions have been entirely separated. The condenser no longer assumes any of the mechanical load. All stresses are carried by the porcelain in compression. Completed bushings of this design have been subjected to severe shock and vibration tests with results that proved the porcelain and steel structure to be adequate.

The oil-impregnated paper structure is made entirely adequate to provide the insulation strength. The porcelain and the fluid oil between the porcelain and the condenser are not relied upon for electrical strength. If, through some accident,



*The insulator, wound of dry paper, is placed in the porcelain housing, and up-ended on this treating rack. While the hollow conductor is heated, a high vacuum is drawn in the interior for many hours after which the structure is filled with oil under pressure and then sealed.*

*Condenser bushings with oil-impregnated insulation are interchangeable between breakers and transformers, new and old.*

the oil should leak out, the insulation strength of the bushing although reduced, would not be entirely lost.

The oil-impregnated paper, which is the real insulation in the condenser bushing, provides the highest insulation strength for a given thickness of any comparable material. Service with insulated cable and capacitors shows that oil-impregnated paper can safely be worked continuously at a stress greater than 100 volts per mil. Tests on samples have been made to stresses as high as 1300 volts per mil impulse voltages, 1.5-40 full wave. (A wave that rises to crest value in 1.5 microseconds and declines to half value in 40 microseconds.) When tested with steep-front, chopped wave, the oil-impregnated paper insulation has withstood voltages as high as 2000 volts per mil.

In the new bushing the thickness of the paper winding is sufficient to keep the dielectric stress through the paper to less than 50 volts per mil average, when subjected to normal line-to-ground voltage. During voltage transients, the stress is increased in proportion to the increase in voltage from line to ground. When the bushing is subjected to standard AIEE, 60-cycle test voltage, the stress per mil radially through the condenser averages less than 200 volts. When tested on impulse at the basic insulation level, corresponding to the voltage rating of the bushing, and using a 1.5-40-ms positive wave, the average stress per mil thickness does not exceed 400 volts.

While the capacitance of oil-impregnated paper is high, making it possible to obtain a high volt-ampere output from the voltage tap, the power factor at both low and high temperatures is small as shown in table I. At room temperature, approximately 25 degrees C, the power factor is 0.006 or less. At 85 degrees C it is 0.01 or less. These power factors of

*There has been no change in the basic method of building up the condenser insulation. However, the adhesive between layers of paper is omitted, which permits more complete removal of the included gases and allows for thorough oil impregnation after the vacuum treatment.*

0.006 and 0.01—which represent only a 65 per cent increase in the power factor hot over that when cold—are the upper acceptable limits on test. The mean of actual test results falls well below these limits.

The low power factor of the condenser bushing means that the internal losses are low and the temperature rise from dielectric losses is small. The small increase in power factor as temperature rises precludes the possibility of temperature instability. Also, it assists in field checking as the results are not so dependent on temperature. The oil surrounding the condenser is free to circulate and carries heat from the condenser to the porcelain for dissipation to atmosphere. High-temperature endurance tests were made in which bushings were immersed for months in oil at 95 degrees C and operated at a voltage of 175 per cent normal. These tests were made to demonstrate the stability of the bushings at high temperature and overvoltage, and their suitability for service in hot climates and with hot transformer oil.

The absence of gas pockets anywhere in the structure, due to the vacuum treatment, greatly increases the voltage at which corona occurs. Because there are no voids, ionization of gases cannot occur. This increases the voltage level at which the bushing can be worked without danger of encountering the losses and insulation-destroying effects of corona. Likewise, it greatly reduces radio interference.

Consideration has been given to the merits of standardization and interchangeability. Whether for circuit breakers or transformers the bushings for 92 kv and above are completely interchangeable. They will, with some few exceptions, interchange with the condenser bushings supplied on previously built Westinghouse high-voltage circuit breakers and power transformers.

*All condenser bushings are power factor tested. The upper acceptable test limits are 0.006 when cold and 0.01 when hot.*

# Solving a Motor-Starting Voltage Problem

***A large pumping motor, a "skinny" supply line provided a tail-wags-dog condition as far as line voltage was concerned. A steadying influence is provided by using the inherent characteristics of a capacitor and an autotransformer. The capacitor provides leading current to offset the heavy lagging current during motor starting, thereby holding the starting voltage up. With the lessening of the starting load, and resulting voltage rise, saturation of the autotransformer holds the voltage down.***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A SERIOUS problem in voltage regulation occurring in connection with starting a large pumping motor on the end of a light transmission line was solved in an unusual manner with a capacitor supplied through an autotransformer. At Roxboro, North Carolina, is a pumping station on the eight-inch extension of the Plantation Pipe Line. The single centrifugal pump at this station is driven by a 600-hp, 2-pole, squirrel-cage motor rated at 2300 volts. Three-phase, 60-cycle power is supplied over a 12.4-kv line of No. 2 copper about 19½ miles long. Normally this line carries a peak distribution load exclusive of the pumping station, of about 444 kw.

It was anticipated that the starting current of this motor might reduce the voltage at the motor terminals to a value less than would provide the necessary starting torque. Starting-torque test data on the motor and the pump, when the line is carrying its densest liquid (fuel oil of 0.867 specific gravity) is given in Fig. 1. From this it is evident that for the motor to have a safe margin of torque during starting, the voltage at the terminals must not be less than 1760 volts. Calculations showed that if the motor was started in the usual manner the voltage would drop to 1388 volts, assuming no other load on the feeder, and a sending-end voltage of 2530 volts. With this deficiency of 1760–1388 or 372 volts, the motor obviously would not be able to accelerate the pump to full speed.

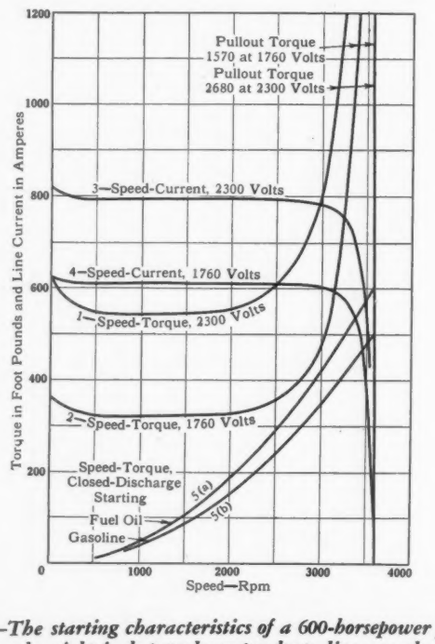



**Fig. 1**—*The starting characteristics of a 600-horsepower pump drive on the eight-inch petroleum-products line are shown as follows:* (1)—*Speed-torque at 2300 volts,* (2)—*Speed-torque at 1760 volts,* (3)—*Speed-current at 2300 volts,* (4)—*Speed-current at 1760 volts, and* (5)—*Speed-torque for starting with pump discharge closed and pumping fuel oil and gasoline.*

Alternative line facilities were considered, but were not permissible from the standpoint of critical materials conservation. The power company, however, agreed to serve the pumping station over this circuit and to deliver a minimum voltage of 1760 during starting, provided a two-section capacitor be installed at the pumping station bus, as shown in Fig. 2. With both sections energized during the starting period the total bank was required to provide a capacitive effect of 1185 kva at 1760 volts. In arriving at this value of capacitor, it was assumed that simultaneously with the motor-starting demand there would also exist on the feeder 80 per cent of the distribution load, or 355 kw at 0.80 power factor.

After completion of the motor-starting period, one section of the capacitor is switched off, leaving an effective capacitor kva of 650 at 2530 volts, this being the calculated voltage attained with this continuously operating capacitor and the motor running at full rated load, and with 20 per cent distribution load. This amount of continuous capacitive kva (650 at 2530 volts) was obtained by using a standard 2400-volt capacitor of 585-kva rating.

Because the required total effective capacitive kva at 1760 volts must be 1185, of which 315 are obtained at this voltage from the continuous-running capacitor, the difference (870 kva at 1760 volts) must be provided by the second or starting capacitor. This section, being in service only during starting

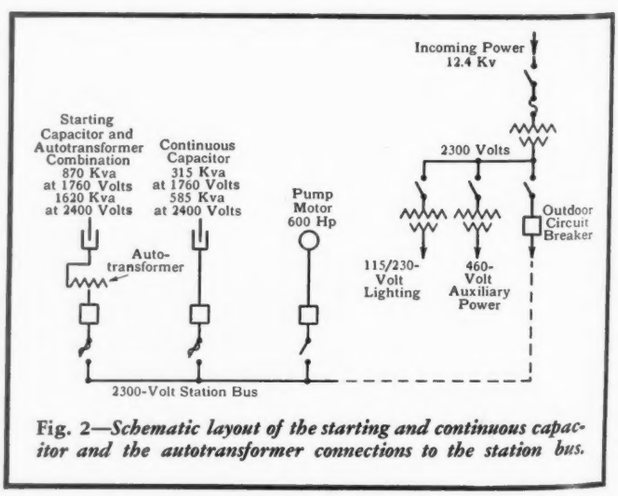



**Fig. 2**—*Schematic layout of the starting and continuous capacitor and the autotransformer connections to the station bus.*

of the pump motor, was designed for intermittent operation.

The capacitors adequately cared for the problem of undervoltage during the early acceleration period, but themselves led to an equally serious problem of excess voltage late in the starting cycle. At the end of the motor-starting cycle, when the motor approaches full speed, its starting current suddenly decreases to a low value, leaving a large net capacitor current on the bus until the starting capacitors can be tripped off. This results in an increase in voltage at the bus, which in turn increases the capacitor current, and this further increases the voltage, the condition stabilizing at a value calculated as about 3200 volts. This overvoltage would be excessive, accelerating lamp burnout, particularly for those lamps near the end of normal life.

Consideration was given the possibility of reducing the overvoltage by removing the starting capacitor as soon as the motor reaches a speed where this capacitor is no longer necessary. This could be done by relaying responsive to change in motor power factor or impedance. However, the capacitor is required until the unit is well up to full speed, after which acceleration is extremely rapid because of the low inertia of the motor and pump and the suddenness with which the motor torque increases after passing the critical range. While such relaying would limit the duration of overvoltage to a fraction of a second, this overvoltage would occur each time the motor is started. Even these brief voltage peaks would be undesirable from the standpoint of service to the pipe line and to other customers on the line.

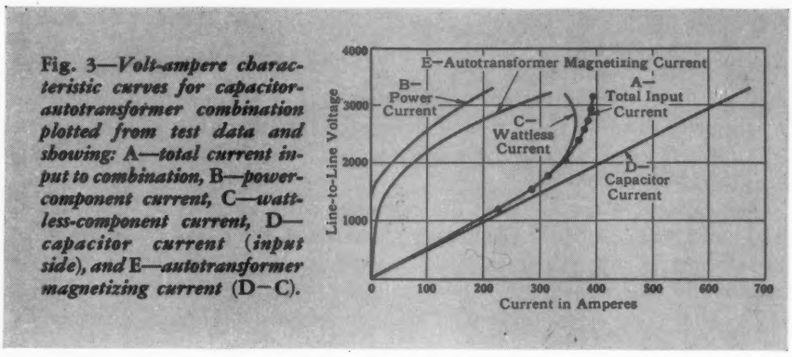



**Fig. 3**—*Volt-ampere characteristic curves for capacitor-autotransformer combination plotted from test data and showing:* A—*total current input to combination,* B—*power-component current,* C—*wattless-component current,* D—*capacitor current (input side), and* E—*autotransformer magnetizing current* (D−C).

## Method of Controlling Voltage Rise

It was, therefore, necessary to provide some means of neutralizing the increase in capacitor current that is inherent with increase in applied voltage. Such control could be effected by introducing, in opposition to the capacitive current, a reactive current small in value at the low voltage existing during most of the starting period, but large when the voltage increases near the end of the starting period, to balance the excess capacitor current at the higher voltage. This could have been accomplished by using in parallel with the starting capacitor an iron-core reactor designed to saturate at a voltage slightly above that at which the capacitor effect is primarily desired.

The method actually used was to supply the starting capacitor through an autotransformer, as shown in Fig. 2. This served two purposes. It provided the necessary lagging current when needed and in addition decreased the size of the capacitor required. An autotransformer ratio was chosen such that a voltage 1.4 times bus voltage was impressed across the capacitor bank, which consisted of standard 2400-volt units. Thus, the leading kva supplied by the capacitor is increased to about twice that provided if the capacitor were operated directly on the bus. Such overvoltage operation is permissible because of the intermittent duty on the capacitor.

To provide the necessary controlled reactive current to limit the effect of the capacitor in the upper range of voltage, the autotransformer was designed so that at 1760 volts the magnetizing current is low, while at voltages above 2400 saturation of the iron occurs, with resultant sharp increase in lagging current.

## Tests Check Installation Theory

To verify the theory of the proposed installation careful tests were made in the factory laboratory. This included a no-load saturation test on the 600-hp motor, carrying the readings up to voltages 200 per cent of normal. The proposed combination of capacitor and autotransformer likewise was fully tested, a series of oscillograms being taken, for which the results are shown in Fig. 3.

The volt-ampere characteristic curve for the combination of capacitor and autotransformer is shown in curve *A*. From each test oscillogram the input power factor was calculated and the total input current was separated into its power and wattless components, curves *B* and *C*, respectively. The net volt-ampere curve for the test capacitor referred to the input side of the autotransformer, is shown in curve *D*. This is a straight line, obtained by actual measurement of the capacitance of the capacitor (5.88 ohms, line to neutral) then deducting the series reactance of the autotransformer to obtain a net resultant capacitance for the combination. The value obtained, referred to the low side of the autotransformer, is 2.83 ohms per phase, line to neutral. For a line-to-line voltage of 2400 on the low side, the corresponding current is 490 amperes. Plotting these two values determines the effective volt-ampere curve for the test capacitor.

The net reactive current, curve *C*, is the resultant of the leading reactive current of the capacitor, curve *D*, and the lagging magnetizing current of the autotransformer; hence, the latter is obtained by subtracting the current values in curve *C* from those on curve *D*, giving curve *E*.

As the voltage increases and saturation of the autotransformer occurs, the magnetizing current drawn by the autotransformer assumes disproportionately greater values, neutralizing to an increasing extent the capacitor current

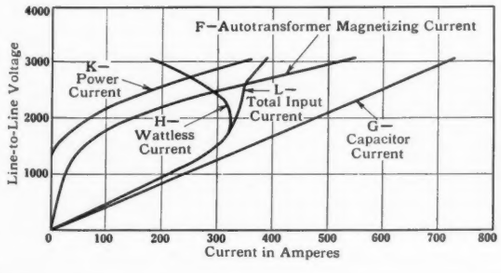



**Fig. 4**—*Volt-ampere curves for combination of standard 2400-volt capacitor and double autotransformer plotted from calculated data. The autotransformer magnetizing current is shown in* F, *the capacitor current (input side) in* G, *the wattless component current* (G-F) *in* H, *the power-component current in* K *and total current input* (K+H) *in* L.

and finally, at about 2700 volts, causing a decrease in the total reactive current.

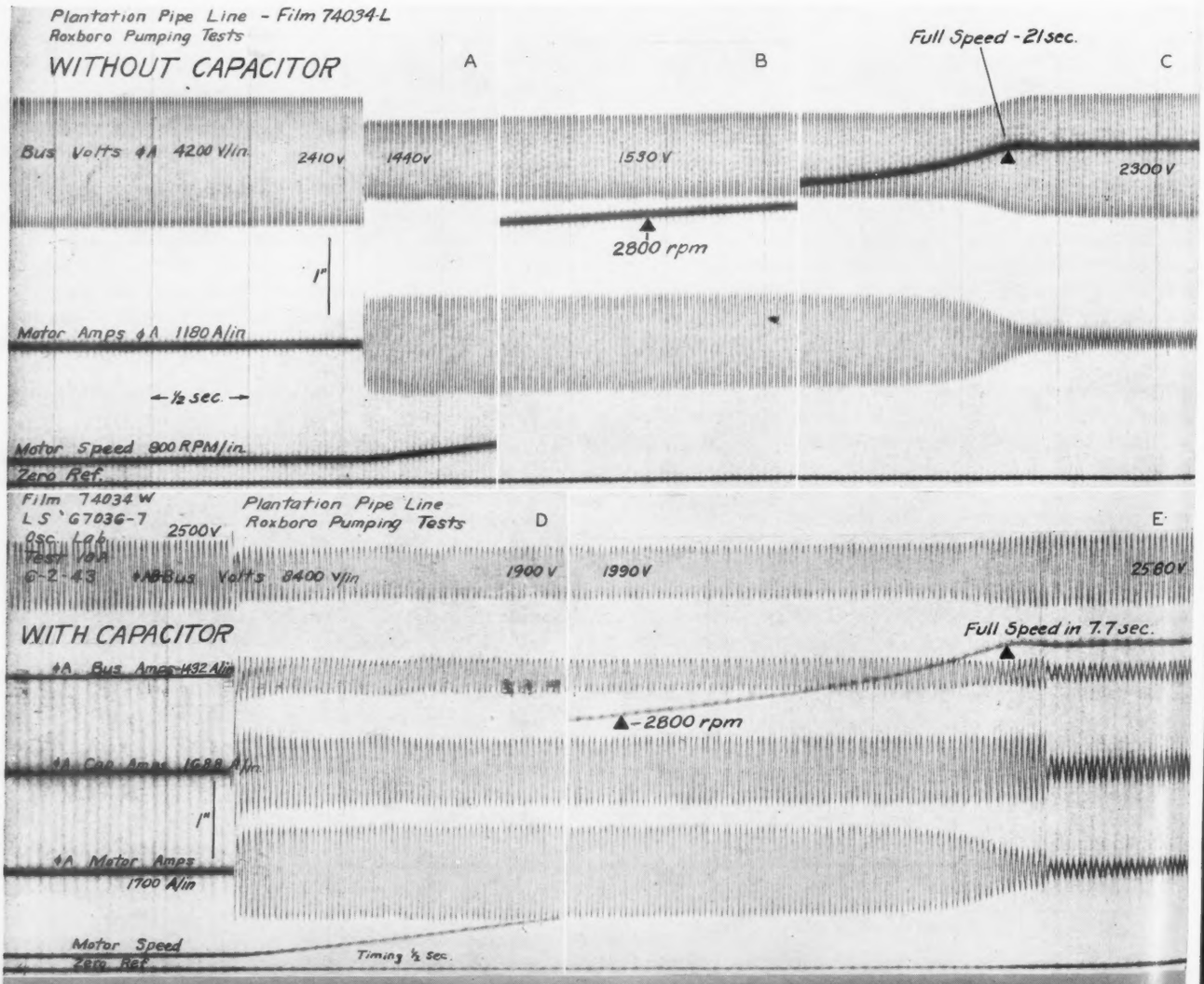
This effect, of course, can be increased by increasing the magnetizing current of the autotransformer. In Fig. 4, curve *F* is a magnetization characteristic calculated for two autotransformers identical with the one tested, connected in parallel to the capacitor.

The capacitive reactance of the capacitor bank alone is 4.92 ohms, line to neutral. The series reactance of the autotransformer is now half the value previously used. The resultant effective capacitive reactance referred to the low side is 2.44 ohms, line to neutral. For a line-to-line voltage of 1760 on the low side, the phase current is 416 amperes. These two values determine curve *G*. In this curve the voltage value and the current value are referred to the low-voltage side of the auto-transformer.

At 1760 volts the magnetizing current drawn by the autotransformer bank is 98 amperes, leaving a net effective capacitive current of 318 amperes, or 970 bank kva at 1760 volts. This approximates the 312 effective amperes for the test capacitor. Either capacitor bank provides about 10 per cent margin of effective capacitive current at 1760 volts, above the minimum requirement for the intermittent capacitor.

Curve *H* is the total reactive current for the combination and is obtained by subtracting the current values of curve *F* (transformer magnetizing current) from those of curve *G* (capacitive current). The power-component current, curve *K*, is constructed by doubling the power-component currents obtained in curve *D*, Fig. 3, for a single autotransformer. Finally, the total current, curve *L*, is obtained by combining the power-current curve *K* and the total reactive-component current curve *H*.

Next, consideration was given to the self-excitation voltage possible with the capacitor banks and the motor connected to the pumping-station bus, the motor at full speed and the bus isolated from the power supply by tripping of the main




***These oscillogram sections show the starting performance of a 600-horsepower motor, with and without capacitors, in the Roxboro station test.***

**Without capacitors the bus voltage (*A*) is reduced from 2410 before starting to 1440 volts. Where motor is started acceleration is relatively slow, and the flatness of the motor speed curve at 2800 rpm (*B*) shows that the excess of motor torque over load torque is slight. Accelerating time is 21 seconds (*C*). A later test with the capacitors in service on a bus voltage of 2500 with no station load, showed a drop to 1900 volts upon starting (*D*). Acceleration (*E*) is considerably more rapid, and the unit attains full speed in 7.7 seconds. Overvoltage at the end of the starting cycle is imperceptible. The bus voltage with the unit running (*E*) is slightly higher than the no-load bus voltage (*D*) because of the leading power factor of the combined load of motor and running capacitor.**

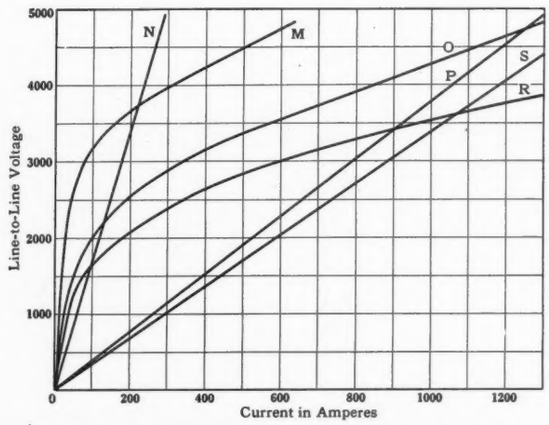



**Fig. 5**—*Curves showing the self-excitation characteristics for 600-horsepower motor and capacitors under the following conditions:* **M**—*excitation current for one motor,* **N**—*capacitor current for continuous capacitor,* **O**—*excitation current for one motor plus single autotransformer* (**M**+**E**), *P—capacitor current for test capacitor plus capacitor current* (**D**+**N**), **R**—*excitation current for one motor plus double autotransformer* (**M**+2**E**), **S**—*current for the intermittent capacitor* (**G**+**N**).

breaker. Two operating conditions must be considered: 1—In normal running operation the 585-kva running capacitor is connected to the bus with the motor; 2—During starting both capacitor banks are in use, and self-excitation can occur with this combination at full motor speed at the end of the motor-starting cycle.

Consider first the running condition. The maximum self-excitation voltage with no-load on the station bus can be predicted by finding the value at which the no-load excitation curve for the motor intersects the volt-ampere characteristic of the continuous capacitor. As shown in Fig. 5, curves *M* and *N*, this occurs at about 3750 volts.

Considering the starting condition, the combined magnetization curve for the motor and test autotransformer is curve *O*, and the volt-ampere characteristic of the effective test capacitor plus the running capacitor is curve *P*. Their intersection occurs at about 4750 volts. The combined magnetization curve for the motor and two autotransformers, curve *R*, intersects the volt-ampere line of the combined intermittent capacitor plus the continuous capacitor, curve *S*, at about 3600 volts. In practice these values are decreased by the loading effect of the losses in the autotransformer feeding the intermittent bank.

### Oscillograph Tests at the Station

Having verified the scheme and determined the practical autotransformer proportions by laboratory test, the installation was made, and field tests of the installed equipment conducted with an oscillograph, to check the performance of the apparatus under service conditions. These tests showed:

1—Without the capacitor the station-bus voltage during starting is inadequate (1530 volts with motor at 2800 rpm). With the two capacitor sections in service the bus voltage is ample (1990 volts).

2—At the end of the starting cycle, before the intermittent capacitor section is disconnected, the station-bus voltage is held to about 105 per cent of its no-load value.

3—With both capacitor sections and the motor connected to the station bus, and the bus isolated from the outside power supply after the motor has been brought to full speed, the self-excitation voltage attains a value of only 2910 volts, about 125 per cent of motor rating. Conditions did not permit measurement of the self-excitation voltage without the autotransformer, but the predicted value for such a combination with no other load on the bus, is in the order of 7500 volts.

This combination of saturating autotransformer and capacitor has been in satisfactory operation at Roxboro station since June, 1943. In this case a motor operates in combination with a relatively large capacitor—the capacitor kva at rated motor voltage being about four times the motor kva. Yet, the installation has handled effectively the problem of overvoltage at the end of the starting cycle, and has reduced the self-excitation voltage from a prohibitive value to one that is practical from an operating standpoint.

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This subject has been discussed in more detail along with other pipe-line problems in Paper 44-40, "The Capacitor—An Aid to Electric Power Service for Pipe Lines," M. A. Hyde and R. E. Marbury, before the Midwinter Technical Meeting of the A. I. E. E., January 24-28, 1944.

## Money-Saving Manufacturing Equipment

Using heat from fuel instead of from electricity for manufacturing processes is frequently a way to save pennies at the expense of dollars. In comparing various sources of heat, too much emphasis is being placed on cost differential per Btu produced. Manufacturing experience has pointed out a definite lesson: the power cost in a product is usually insignificant in comparison to its total value.

• • •

A certain mold, electrically heat treated in a controlled atmosphere, cost $250. If heat treated in a fuel-fired furnace the cost would have been $330. Although the heat cost of the electric-furnace operation was more, the total fuel cost chargeable to this mold was only four per cent. This was much more than offset by the work necessary to remove the heavy scale formed in the fuel-fired furnace.

• • •

A die for drawing of brass consisted of a slot one half inch long but only twenty thousandths of an inch wide in a piece one half inch deep. To machine such a narrow slot would have been costly. The die was made by brazing together, in an electrically fired furnace, two easily machined pieces. The cost of electric power was insignificant compared to machining costs.

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Parts to be forged were brought to forging temperature in an induction coil, which, because of the speed of heating, resulted in almost no scale. The absence of the abrasive scale lengthened the life of the $2500 forging dies by one fourth, which fully justified the costlier power source.

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The terminals for heavy electrical connections made of flexible copper braid were applied by electric-resistance brazing. The result was better electrical conductivity, a neater product, elimination of brittleness encountered with soldered joints, and a reduction in overall cost by one half.

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The uncured material for a molded handle is preheated by high frequency before being placed in the mold. The curing cycle is reduced from ten minutes to two.

# Stories of Research

## Weather a la Carte

Not so very long ago itinerant characters toured the central states with various and sundry equipments, among which was usually numbered a cannon. With prayers, fasting, and firing of cannon, these rain-makers tried to do something about the weather as well as talk about it. Today exact weather conditions are being produced in miniature by Dr. L. J. Berberich and his associates at the Westinghouse Research Laboratories.

It is necessary to have those varying conditions of weather on tap in order to study the characteristics of the electrical equipment on airplanes under different weather conditions. Will insulation that is satisfactory when dry and at ground level be equally satisfactory in the cloud banks at more than 30 000 feet? Will ice and snow cause the voltage to arc over the insulated gaps in aircraft power systems? To test these things a miniature weather chamber was built.

Clouds are created in a few seconds by pouring liquid air into warm water. The liquid air boils so violently upon contact with warm water that minute particles of the water are carried up with the air as it evaporates and form a dense cloud. By a slight pressure differential, the cloud is carried into the test chamber through a tube. Pumping out the test chamber (really a large glass flask) simulates the low pressures encountered at altitudes as high as 65 000 feet. The sub-zero temperatures of the atmosphere at these altitudes are duplicated by surrounding the walls of the flask with a mixture of dry ice and alcohol. Cooling the test chamber below freezing causes snow crystals to form in the tiny cloud, and they fall onto the insulation being tested.

Tests show that moisture in the frozen form, such as ice and snow, does not lower the breakdown voltage of air or the flashover voltage of an insulating surface. Also, moisture in the vapor form does not have any significant effect on these two electrical phenomena. However, moisture in the cloud or suspended droplet form lowers the breakdown strength of small air gaps, and moisture condensation on the surface of an insulating material results in a marked lowering of the flashover voltage.

*With liquid air and warm water Mr. A. M. Stiles produces clouds in tiny altitude chambers where plane parts are tested.*

This new weather-a-la-carte chamber enables the designer to determine the safe minimum of insulation and air gaps.

*Using this warlike distaff, Dr. Alois Langer spins a gossamer thread of quartz one thirty-thousandth of an inch in diameter.*

## The Crossbow—an Instrument of Fineness

In these days of superaccuracy, the crossbow is considered a somewhat crude device. Nevertheless, Dr. Alois Langer, of the Westinghouse Research Laboratories, makes use of a crossbow and arrow to produce a filament of quartz one thirty-thousandth of an inch in diameter.

To calibrate properly the magnifying powers of an electron microscope it is necessary to have a standard of known minute thickness so that the magnifying power of the several stages can be resolved and measured. To produce such a standard is difficult.

Fused quartz can be heated and drawn into filaments of quite small diameter. The problem involved is to draw out the bead of fused quartz before it can cool and solidify. The need is for an instrument that will supply a high initial velocity. This need is supplied by a crossbow and arrow.

One end of a piece of quartz rod was fastened to the crossbow frame, the other end to the arrow. With a blow torch, a small bead of the quartz rod was fused, and while in the fused state the trigger was released. The arrow, speeding some 80 feet in swift flight, drew out the small molten quartz bead into a long filament before it could cool. Sections of this thread of quartz, checked against an optical grating, proved to have the desired diameter.

## Lightning Strikes Again—and Again

THE FALLACY that lightning never strikes twice in the same place has been disproved time and again. In fact, a new score card has been devised by Dr. Leo Finzi, of the Westinghouse Research Laboratories, to record the strikes in this Jovian game.

*The simple recorder held by Dr. Finzi is used in conjunction with arrester devices. A small portion of the current is detoured from the grounding circuit and passed through this instrument. As shown here, each successive surge through the recorder burns off the foil point through which it passes and leaves on the plastic sheet an indelible record of its passing.*

It would seem that such an instrument must be of necessity of great size. Actually, it consists of two strips of thin metal foil, such as formerly covered cigarette packages, placed between two sheets of plastic. The whole arrangement can be palmed like a deck of cards. One piece of foil has a straight edge. Very near to this straight edge is the saw-tooth edge of the other strip of foil. When this device is clamped to a lightning-arrester ground lead, a small portion of the current of the lightning discharge is passed between the plates. This small current, jumping the gaps between the strips of foil, blackens the plastic and leaves an indelible record of its passing.

The accuracy of the recorder depends on the uncanny faculty of lightning to select invariably the shortest gap between the two pieces of metallic foil. One saw-tooth may be nearer the other strip of foil by less than one ten-thousandth of an inch, but the charge will unerringly select that path. Of course, in passing it will burn away the point so that some other point is then nearest the other piece of foil. The next stroke will select that particular saw-tooth, and so on, leaving a clear and precise record of strokes that hit the transmission line in the night (or day). Not a protective device, it merely is a method of recording the number of operations of the smooth-operating lightning arresters whose efficient protection might otherwise pass unacknowledged.

A laboratory development, it is not available commercially.

*From the impact of high-velocity bullets to dynamic loading of warehouse floors seems a long and illogical jump. However, the forces involved, and their distribution, are found to be sisters under the skin. The bullet, striking a plastic plate coated with a special lacquer known as Stresscoat, leaves a characteristic pattern of cracks in the lacquer. These cracks are interpreted to show the direction and magnitude of the forces. Such studies show the previously held theories relating to projectile impact and dynamic loading to be wide of the mark. They show the way to armament improvement and an accurate approach to dynamic floor loading and similar problems.*

## Attack One Plating Problem; Solve Many

MANY of our airplanes fighting the Zeros and Messerschmitts are equipped with gold-plated instruments. For a time it seemed that gold was the only answer to a tough engineering problem. Certain copper or brass parts of instruments, such as studs, that carry high-frequency currents, must not only have high corrosion resistance, but also high electrical surface conductivity because of skin effect. Nickel would normally be used to provide the necessary anti-corrosion protection, but its electrical resistance is too high. Engineers turned to gold, which, although costly, is non-corrosive and satisfactorily conducting.

Electrochemists attacking this problem came up with an answer that not only neatly disposed of this particular worry but also provided a plating technique valuable in many applications unrelated to the original need. Special plating anodes are made of an alloy of copper, tin, and zinc. With these soluble anodes, copper and brass parts are plated, using a standard plating practice.

The results are truly amazing. The plated surface has electrical conductivity necessary for high-frequency applications, and a corrosion resistance far superior to nickel. Further, the finish is mirror-like, being surpassed in this respect only by silver itself. In abrasion, the surface is roughly twice as good as the usual nickel coating. The new plating is entirely non-magnetic (which nickel isn't) and is easily soldered, a fact of great value in many electrical applications. Furthermore, the new plating process has great "throwing power," i.e., the deep interior surfaces of cavities are plated with much more uniformity than is possible with nickel plating, heretofore regarded as standard.

*Emerging from this tumbler, the plating on instrument parts is as good as gold, in fact replaces gold on many sea-borne parts.*

# Common Circuits for Metal Rectifiers

*The engineering worth of the metallic rectifier needs no further exposition. The 150 million discs placed in service on this continent alone establish its position. Having a capacity range of 100 million to one, certain circuit characteristics must be considered when selecting the one that will exploit the inherent capacity of this type of rectifier to the full. Here are given the principles that form the basis for selecting one type of circuit in preference to another.*

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*Section Engineer*
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TURNING sine waves into direct current has become a big part of electrical business, with many kinds of devices for doing it and many ways by which they can be connected. The basic schemes of connections for dry-disc and metallic rectifiers are few, and each has its own special points of advantage and disadvantage.

Simplest of all rectifier circuits is the half-wave connection, shown in Fig. 1 (a). This circuit is frequently used with tube rectifiers, but less commonly with metal rectifiers for reasons that will appear. The half-wave connection permits one half cycle of current (positive) to pass through the rectifier and the load, while the other half cycle (negative) is blocked. This results in the output wave shown. If the load is resistive, the rectifier must be able to withstand the full voltage for the blocking half cycle and be able to carry the load current for the other half cycle. To obtain a given average d-c voltage then requires roughly twice that much voltage in the transformer so that the back voltage on the rectifier is approximately twice the average load voltage. These figures take no account of rectifier losses, transformer regulation, or form factor. The rms value of the load current, which is what the rectifier must be able to handle, is 1.57 times the average value.

When the load includes a counter emf, such as a battery or a capacitor, this voltage is added to the transformer voltage during the off half cycle and must be blocked by the rectifier.

A disadvantage of this circuit is that the direct current delivered by the rectifier also passes through the transformer secondary, so that the saturating effect of the direct current must be considered in the design of the transformer.

Two half-wave rectifiers can be combined so that both halves of the a-c wave are rectified, as in Fig. 1 (b). This is usually called the full-wave connection. If each half of the transformer secondary is the same as the full secondary in (a), then the average value of the output voltage is twice as much for (b) as for (a). Also, the average value of current is doubled, so that the watts output is increased four times. The back voltage on each of the two rectifiers, however, will be the full transformer voltage, roughly twice the load voltage, or twice as much as for (a), and each rectifier in (b) must then have twice as many discs in series as in (a). The complete rectifier of (b) is four times as large as that of (a), and the output per disc is, therefore, the same.

A disadvantage of the full-wave circuit is in the relatively poor utility factor of the transformer, because only half the secondary functions each half cycle. Also, the provision of the center tap adds to the cost. Saturation of the transformer is eliminated. Each half of the secondary does carry a d-c component, but in opposite directions, so that the saturating effect is nullified.

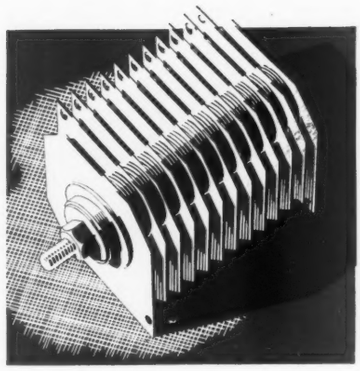
Most common of metal rectifier connections is the well-known Graetz, or bridge connection, Fig. 1 (c). A trace of the path of the load current through the rectifier in the directions indicated by arrows shows that one half cycle flows through two of the four legs in series, while the succeeding half cycle flows through the other two legs. If the transformer secondary in (c) is the same as in (a), inasmuch as both half cycles are rectified, the output voltage and current are doubled and the watts output increased four times. Each rectifier section or leg must withstand the transformer voltage, so each leg is the same as the single leg of (a). Hence, the rectifier is four times the size of the rectifier in (a).

The watts output per disc for (a), (b), and (c) is identical. Consequently, no advantage accrues from the use of either the half-wave or full-wave connection as against the single-phase bridge from the standpoint of economy of material. The better utility factor of the transformer in the bridge connection and the elimination of the center tap explains why the bridge is used so extensively. Frequently bridge rectifiers are connected directly to the a-c supply line without making use of an intervening transformer.

The full-wave connection is required only when maximum efficiency is desired at voltages half way between the maximum efficiency points for the bridge. The output voltage of the full-wave connection is roughly half the total transformer voltage, while the input and output voltages of the bridge connection are approximately equal. Hence, if the output rating per disc in the bridge connection is six volts, with maximum efficiency points at 6, 12, 18, etc., volts, the rating of the same disc in the full-wave connection is three volts, if the discs are to withstand the same transformer voltage. Maximum efficiency points then for the full-wave connection come at 3, 6, 9, 12, etc., volts.

The bridge can be extended to any number of phases. Next to single phase, three phase is, of course, most common. This is

shown in Fig. 1 (d). The rectifier can be considered to be made up of three single-phase bridges, with each leg common to two bridges. The advantage of the three-phase connection, of course, is the much improved output wave form shown and the higher efficiency obtained on the basis of average values of output. In this circuit each leg of the rectifier carries the entire load current for one third cycle and blocks the line voltage for two thirds cycle.



Other three-phase circuits having the same output wave form as the bridge connection are the diametric, Fig. 1 (e) and the double wye, Fig. 1 (f). These circuits are much less frequently used for metal rectifiers than is the bridge connection.

The diametric connection is like the full wave in requiring more expensive transformer construction than the bridge connection and having a poorer utility factor for the transformer. Each leg of the rectifier, moreover, carries the load current only for one sixth of a cycle, so that for the same average output the current per leg has a higher rms value, causing increased heating. Because discs must be rated according to the watts dissipated, the diametrically connected rectifier cannot be rated as high as the bridge-connected rectifier. As in the full-wave connection, however, maximum efficiency points can be obtained at voltages half way between the points of maximum efficiency for the bridge connection.

In the double-wye connection the interphase transformer causes the two wyes to operate in parallel, so that each leg of the rectifier carries one half the total load current for one third of a cycle. Thus, for the same average output, the current per leg has a lower rms value. Again, maximum efficiency points can be obtained half way between the maximum efficiency points for the bridge rectifier. A disadvantage, however, is that for the same output voltage, about 15 per cent more a-c voltage must be impressed upon the rectifier in the double-wye connection, thus increasing the back voltage.

While the diametric and the double-wye, three-phase circuits are but seldom used for metal rectifiers, there are applications where the location of the maximum efficiency point or other special needs suggest their use. In general, these two circuits are used chiefly in connection with mercury-arc rectifiers. Here the disadvantage and extra cost of center-tapped transformers or separate interphase transformers is offset by the simplification of the insulation problem in that all cathodes are tied together and do not have to be insulated one from another.

For small-current, high-voltage applications, the voltage-doubling circuit or some other form of voltage multiplier can be used. In the standard voltage-doubling circuit, shown in Fig. 1 (g), a full-wave output is obtained by replacing two of the legs of the bridge rectifier by capacitors. The per cent ripple in the output voltage, however, is not fixed as for previous connections but is a function of the load resistance and the size of the capacitor.

To simplify this brief discussion, resistive loads only have been considered. Addition of capacity, inductance, and counter voltage in the load, particularly for the single-phase connections are important in the design of metal rectifiers.

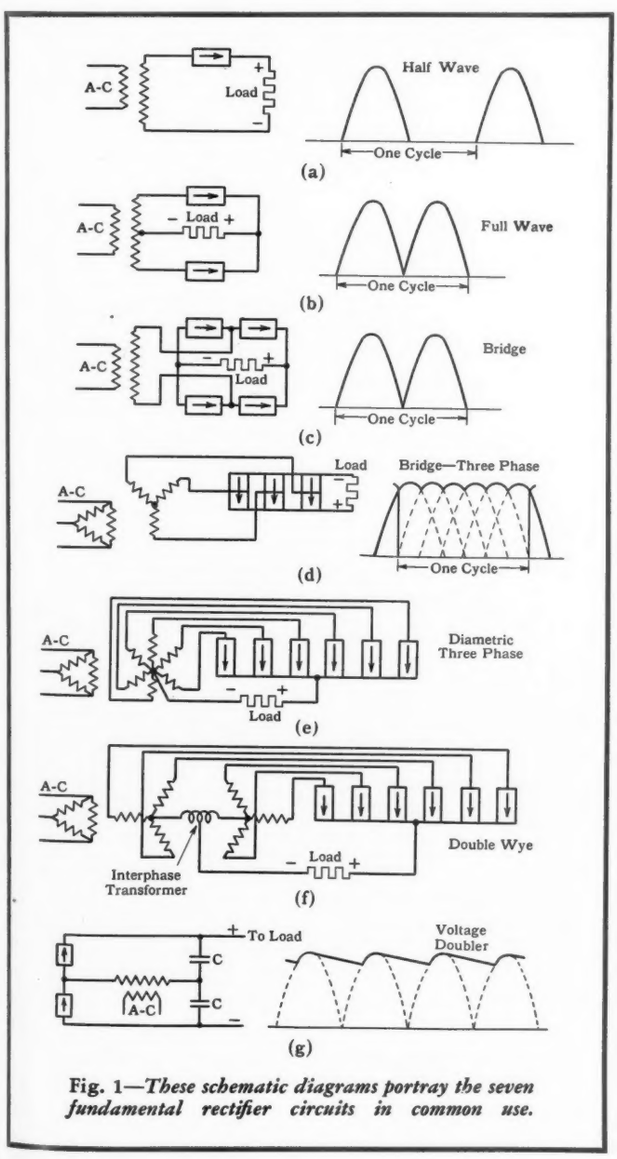



**Fig. 1**—*These schematic diagrams portray the seven fundamental rectifier circuits in common use.*

## Rectifier Versatilities

Copper-oxide rectifiers are usually associated with high-current, low-voltage applications. Such, for example, is the installation providing 240 000 amperes at 6 volts for tin electroplating. This is made up of 48 units, each delivering 30 kw.

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These dry-disc rectifiers can also be used for low-current, high-voltage work. One is being built now to deliver only one-quarter ampere at 70 000 volts. This will be accomplished by using 24 000 of the 1½-inch discs. The atmosphere around this rectifier will be both hot (150 degrees F) and corrosive. For this reason the rectifier will have to be completely enclosed and forced-air cooled, using water-cooled heat exchangers. The need for an extremely long life and the difficult service conditions dictated the use of a metal rectifier.

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At the other end of the rating scale is the minute copper-oxide rectifier used in high-frequency instruments. It is rated at one thousandth of an ampere at one volt and is but 3/32 inch in diameter. A bank of four in their Micarta housing is small enough to be covered by a thimble.

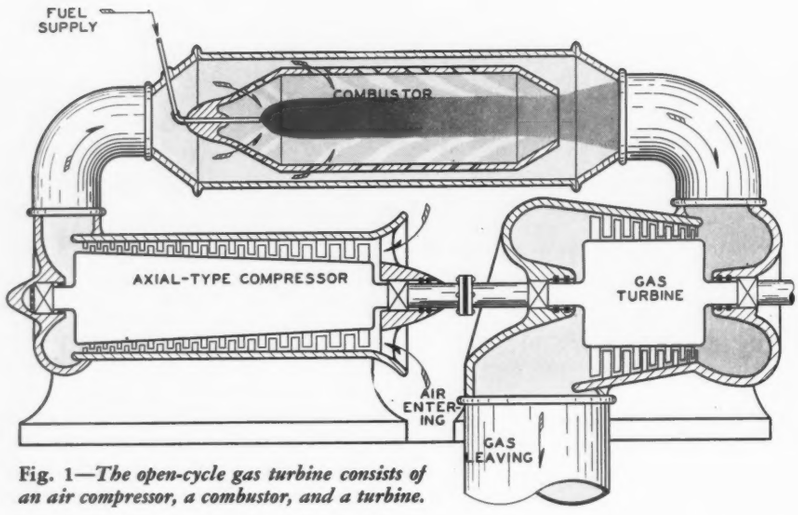


**Fig. 1**—*The open-cycle gas turbine consists of an air compressor, a combustor, and a turbine.*

***Although the gas turbine has been the plaything of Hero, Newton, comic-strip artists, dreamers, jet-propulsion enthusiasts, and many sane, capable engineers, there is still but a handful in service, and not many engineers know its principles. The difficulty has been in building a turbine that can develop more power than is consumed by its own air compressor. Only at high temperature can the turbine win by a practical margin. War-born metals may be the vitamins that will enable the turbine to forge ahead. The gas turbine has already become a reality; its future has many fascinating possibilities.***

# The Gas Turbine—Harness for Hot Air

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IN FUNCTION the gas turbine closely resembles the internal-combustion engine. In each, air is compressed, liquid fuel is injected and burned, and finally the high-temperature gases under pressure are expanded to atmosphere, producing in the process useful power in excess of that required to compress the air. The internal-combustion engine uses one structure for all three functions, i.e., the air is compressed, liquid fuel burned, and gases are expanded all in a cylinder. Because the engine makes one structure do all three jobs it must do them successively, so that the power output is cyclically interrupted. The gas-turbine power unit, on the other hand, separates the three operations, assigning a separate specialized mechanism for each. The air is compressed in a physically separate compressor, the liquid fuel is burned in an adjacent combustor, while the gas turbine itself serves only to expand the gases of combustion, enabling it to drive the compressor and some useful load. (Hence the name *gas turbine.* Petroleum, not gas, is the fuel.) By this system each of the three elements operates continuously, so that the power flow from the gas-turbine unit is continuous. Because each can be designed for a single purpose and because the speeds can be high the total weight of a gas-turbine power unit can be much less than that of an internal-combustion engine.

The boiler in a steam plant is not thought of as being a compressor but that is essentially what it is—a means of delivering steam at high pressure. The combustion area under the boiler corresponds to the combustor of the gas turbine and the steam turbine corresponds to the turbine part of the gas-turbine power unit.

### What the Combustion-Gas-Turbine Power Unit Is

The gas-turbine power unit in its simplest form consists of three major elements: an air compressor, a liquid-fuel combustor, and a turbine. These are shown in true relative size in Fig. 1 and schematically in Fig. 3. The turbine resembles the straight reaction, non-condensing steam turbine, and in similar manner produces useful mechanical power by expansion of hot gas through several stages of stationary and rotating blades. The volume of gas is many times greater than in steam turbines; also, the pressure and temperature drops are much less. For these reasons the gas-turbine blades more nearly resemble airplane-propeller blades than conventional reaction steam-turbine blades. The relatively large gas volumes and small temperature and pressure differences are cardinal facts to remember in understanding the gas-turbine cycle.

The type of air compressor depends solely on certain practical considerations, such as efficiency, cost, weight, and bulk. At present the axial-flow compressor is by all odds the most promising of providing the large amount of air under pressure. It resembles a straight reaction turbine; in fact it is essentially a reaction turbine in reverse. This type of compressor, in small physical size, efficiently handles the large volume of gas involved.

The combustor is the burner in which fuel oil is burned with sufficient excess air to bring the temperature of the gases down to that acceptable to the turbine blading. The combustor is small because its rate of heat release is many times that of the conventional steam boiler, where the heat must be transferred through the tube walls to generate steam instead of being used directly in the turbine.

The three major elements—compressor, combustor, and turbine—comprise the power-producing unit that is connected to a generator or shaft for transmitting the useful power output, and to a starting device. Some external starting means, such as a motor or compressed air, is required, because the combustor cannot provide hot gas under pressure to drive the turbine until it receives air from the compressor, which in turn derives its power from the turbine. Hence, the cycle is not self-starting.

The simple gas-turbine cycle uses no intermediate medium —such as water—as does the steam cycle. Hence the boiler,

which is the largest single piece of equipment in the steam power plant, is replaced in the gas cycle by a compressor and combustor. As a consequence the power plant is much smaller and more compact. The simple open-cycle combustion gas system exhausts to atmosphere and requires no cooling water, so that the steam condenser of the condensing steam cycle also is avoided. The simple-cycle gas-turbine plant has a further advantage in that it can be located without reference to a source of suitable cooling water.

### Practical Aspects of the Cycle

Inventors have for years been intrigued by this cycle; the first patent was granted more than 150 years ago. Early inventors were unsuccessful in building units efficient enough to drive their own compressor, let alone supply any useful net output. The cycle was perfectly sound; these early inventors lacked certain essential tools. They lacked materials capable of operation at the necessary high temperature and they lacked turbines and compressors of adequate efficiency.

Today, the story is changing. The metallurgy of high-temperature materials has steadily improved and further gains are to be expected. The maximum operating temperature of a given material is largely a question of the useful life required from the apparatus. For a life of relatively few hours, such as might be satisfactory for some military needs, temperatures in the region of 2000 degrees F are allowable. For heavy-duty (long-life) apparatus, the allowable temperatures on the same materials would be much lower. The wartime developments in metallurgy will undoubtedly produce materials capable of operation at temperatures that would have been unobtainable for many years in peacetime.

In the gas-turbine cycle the useful power output depends upon a high efficiency from both turbine and compressor.

### The Gas Turbine Essentials in a Nutshell

(a)—The simple gas-turbine cycle comprises three devices: an air compressor, a combustor, and a turbine. The fuel is petroleum. The hot gases of combustion and heated excess air drive the turbine, which exhausts to atmosphere.

(b)—As compared to steam, the gas-turbine cycle uses very large gas volumes and small temperature and pressure drops. The gas-turbine cycle uses from four to six times more air than required for perfect fuel combustion, instead of 20 to 25 per cent more in the steam cycle. Excess air keeps the turbine inlet temperature within acceptable limits.

(c)—In the simple open gas-turbine cycle the combustion gases pass directly through the turbine; there is no heat transfer to a second medium, as water. In the closed cycle a heat exchanger is required in which the recirculating gases give up their heat to cooling water before they enter the compressor. In the externally fired closed cycle the heat from the combustion gases is transferred to another medium that is recirculated at high pressure.

(d)—The gas turbine is not self-starting.

(e)—The simple gas-turbine cycle requires no water, either for use in the cycle or for cooling. Likewise no boiler or condenser.

(f)—The gas turbine is not reversible.

(g)—Successful coal-burning gas turbines await future development.

(h)—Blade and piping dimensions at present limit practical open-cycle units to about 7500 kw, although present developments may raise this figure. For larger outputs the closed-cycle system must be used. The efficiencies of the open and closed cycles do not differ appreciably.

(i)—The efficiency of a gas turbine at full load is satisfactory and the control is simple, but at partial load the efficiency of the open-cycle gas turbine falls off sharply unless complicating features are added.

(j)—Time (i.e., service life) is an important dimension in considering the gas turbine. The length of time a given material can function at high temperature declines rapidly as temperatures are increased.

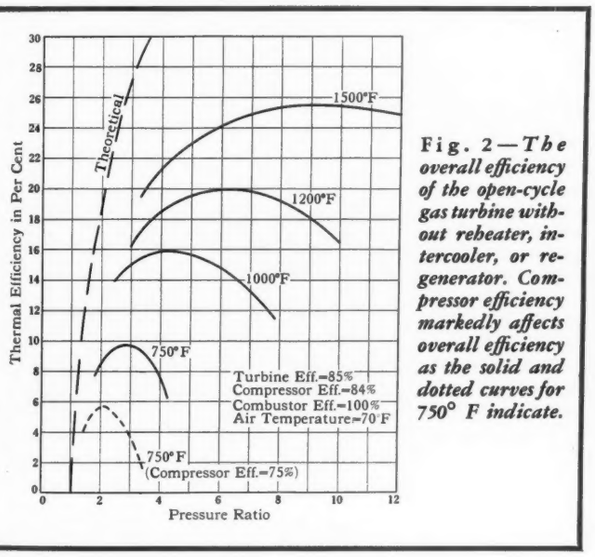



*Fig. 2—The overall efficiency of the open-cycle gas turbine without reheater, intercooler, or regenerator. Compressor efficiency markedly affects overall efficiency as the solid and dotted curves for 750° F indicate.*

The available power is the difference of two fairly large quantities, the total turbine output and the energy consumed by the compressor in compressing the air. When the unit operates at a top temperature of 1200 degrees F, for each horsepower output, the turbine develops 3.95 hp of which 2.95 is required to drive the compressor. A reduction of one per cent in the efficiency of each of these elements reduces the useful output by seven per cent. The power available also decreases sharply as the temperature of the gases entering the turbine is lowered.

Maximum efficiency is obtained at relatively low ratios of inlet to atmospheric exhaust pressure (14.7 pounds per square inch absolute) of the order of six for 1200 degrees F, as Fig. 2 shows. This means that turbine-inlet pressures in the open cycle are low, i.e., pressures of less than 100 pounds per square inch absolute. For appreciable power, therefore, and with these low pressures, gas volumes must be large and turbine blades must likewise be large.

As table I shows, the pressure in an open-cycle gas turbine is low as compared with that in the steam cycle. The energy per pound of gas is small and the flow of gas is large; 510 000 pounds per hour for the simple-cycle gas turbine as compared to 52 500 pounds per hour of steam to the steam turbine, or a ratio of about ten to one. The large volume and low pressure of the combustion gases to the inlet of the gas turbine means the piping and blading of the gas-turbine inlet are large compared to the steam turbine. The ratio of exhaust to inlet volume is small for the gas turbine. This makes a balanced blade path unlike that of the steam turbine, in which the exhaust volume is 250 times the inlet volume.

### Cycle Arrangements for Improved Efficiency

The efficiency of the simple open-cycle gas-turbine system is attractive only at high temperatures, as Fig. 2 shows. The gas-cycle efficiency can be improved to a marked degree by various combinations of several practical but complicating additions, such as regenerators, intercoolers, and reheaters. In the regenerating gas cycle a heat exchanger (regenerator) is used to transfer some of the heat in the exhaust gases (which leave the turbine relatively hot, of the order of 600 degrees F) to the compressed air before it enters the combustor. This is illustrated in Fig. 4. Heating the air ahead of the combustor requires less fuel, and the cycle efficiency is improved. The amount of heat thus transferred or conserved depends on the size of the heat exchanger, which is contingent on gain in efficiency balanced against the cost of a heat exchanger. Calculations indicate that at 1200 degrees F inlet temperature the maximum recovery will not exceed three quarters of the available heat from the gas-turbine exhaust. This represents a heat exchanger volume of about 0.30 cubic foot per kilowatt of turbine output.

Intercooling is illustrated in Fig. 5 in combination with regeneration. As the name implies, it consists of removing the heat of compression from the air passing through the compressor. The purpose of the compressor is solely to provide a given amount of air at a given pressure to the combustor. The lower the temperature of the air being compressed the less power required to compress it.

Ideally a large number of intercoolers would be desirable. Probably only one or two stages are economically practical. Other conditions remaining the same, one stage of intercooling reduces the compressor work by some 15 per cent. This increases the portion of the turbine capacity available as useful output and improves the cycle efficiency.

A supply of water becomes a necessary part of the cycle when intercooling is used. The water is circulated through the intercooler and cools the air. Reheating consists of adding heat to the gas as it passes through the turbine, Fig. 6. In principle, the gas-turbine reheat cycle is the same as the reheat cycle used in steam plants. In practice, however, it will bear little resemblance. Reheating in the gas turbine consists of burning fuel directly in the gas, which is about 85 per cent unburned air, passing through the turbine. The large amount of large steam piping and considerable heat-transfer surface in the heat exchanger of the steam reheat cycle will be replaced by a reheating combustor which may possibly be located within the gas-turbine casing. Here again the practicable number of reheats is limited.

Reheating and intercooling increase the amount of useful energy per pound of working gas passing through the system, thus reducing the number of pounds of working gas circulated. Therefore, the size of piping and blade path in the compressor and turbine are reduced. In combination with a regenerator they aid by increasing the terminal difference across the heat exchanger, for a given size exchanger, or permit a smaller heat exchanger to transfer the same amount of heat. At partial loads they increase the efficiency considerably.

In table II the different cycle arrangements are compared on the basis of the power requirements of each major element, using the capacity of the generator as unity.

An idea of the value of various combinations of regenerating, reheating, and intercooling, and a general idea of the possible applications of this cycle are provided by Fig. 9. The temperature range of 1000 to 1500 degrees F has been chosen because applications at temperatures much below 1000 degrees are considered impractical. Early applications for heavy-duty, long-life apparatus will probably not exceed temperatures of 1200 degrees F with 1500 remaining for future developments in metallurgy.

The temperature of inlet air to the compressor has a marked effect on cycle efficiency, as shown in Fig. 10. The colder this inlet air, the higher the cycle efficiency and capacity. In the simple open cycle, changing the inlet air temperature ten degrees F changes the cycle efficiency three per cent and the capacity by about four per cent.

### Comparison of Steam and Combustion Gas Cycles

From a purely theoretical standpoint the combustion-gas-turbine cycle holds forth greater promise of efficiency than the steam cycle. Of more value as a basis of judgment are the thermal efficiencies obtainable in practical applications, of which an estimate is given in Fig. 11. Above 1000 degrees the gas-cycle efficiency increases approximately three times as fast as the steam-cycle efficiency for a given increase in turbine inlet temperature.

## The Simple Gas Turbine and the Successive

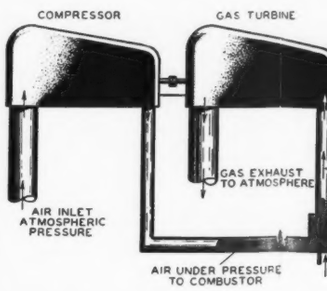



**Fig. 3**—*The simple open-cycle combustion gas-turbine power plant consists of a combustor and a turbine which drive a compressor and a generator. A starter always required, is shown only in this figure.*

**Fig. 5**—*Further increase in efficiency is obtained by extracting some of the heat from the air during compression by an intercooler. With a single intercooler, as much as 15 per cent less power will be required by a representative axial-flow compressor.*

**Fig. 4**—*Efficiency is increased by a regenerator, which heats the air to the combustor with some heat extracted from the turbine exhaust gases.*

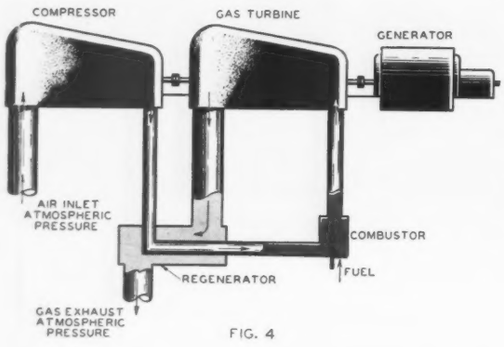



FIG. 4

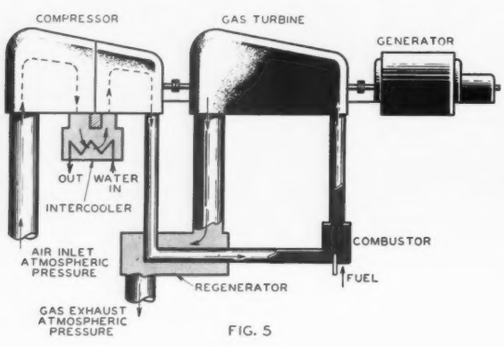



FIG. 5

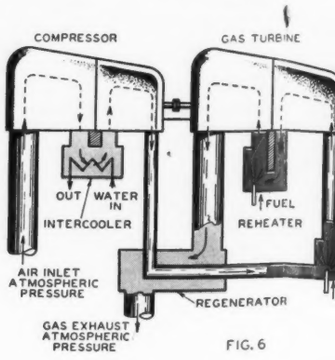



FIG. 6

### The Closed Cycle Permits Larger Units

Because of the large blade dimensions and the large piping required for the open-cycle, gas-turbine power plant, its maximum net output rating of a practical open-cycle, single-flow combustion gas turbine is about 7500 kw at either 1800 or 3600 rpm. However, the injection of liquids presents a theoretical possibility of extending this limit considerably.

The closed cycle offers a way to increase the maximum-size limitation. If the absolute pressure of the working gas is multiplied by ten, the size is divided by ten. In the closed cycle the recirculated gas is worked at a relatively high pressure, as compared to the open cycle, which reduces the physical size of compressor and turbine. To lower the temperature of the gases, before they enter the compressor, cooling water is required in the closed cycle. The heat absorbed by the cooling water is equivalent to that removed in the condenser of a steam unit of equal capacity.

The Escher Wyss closed-cycle system is shown in Fig. 7. The working medium (air, hydrogen, or other gas) operates at a relatively high pressure in a closed, recirculating circuit. The heat from the products of combustion is transferred to the recirculated gas which then expands in the turbine to a lower pressure. The gas heater in this cycle corresponds to the boiler in the steam cycle. Because the gas heater operates on a gas-to-gas transfer it will be larger than the modern steam boiler for a given efficiency level. This cycle is similar to the steam cycle; the main difference is in the working medium, which does not undergo a change of state.

In the closed cycle the compressor inlet pressure will be maintained at approximately 150 pounds per square inch with a discharge pressure of some 600 pounds. This high pressure reduces the size of turbine and compressor by a large amount and should permit ratings approaching those in the steam cycle.

Because this closed cycle keeps the products of combustion out of the turbine and compressor circuit, the problem of using coal as a fuel should be much simpler of solution than in those cycles that circulate the products of combustion.

A type of closed cycle under development by Westinghouse is illustrated in Fig. 8. In this closed cycle a separate gas turbine and compressor are used to pump up the cycle on which the main gas turbine and compressor operate. Here again a high pressure of about 600 pounds would be used with a compressor inlet pressure of 150 pounds. The main gas turbine and compressor would be small as they operate at much higher pressure.

Unlike the Escher Wyss system, this cycle is internally fired. The products of combustion pass through the gas turbines and main compressor. Enough make-up air is continually supplied to maintain pressure and support combustion. It is supplied by a compressor driven by gas at high pressure and temperature bled from the circulating system and expanded through a second gas turbine. In this cycle the large gas heater required by the Escher Wyss cycle is eliminated. It does entail an extra gas turbine and compressor to build up the pressure within the closed system. Also any solid matter from the fuel must be removed from the system.

Reheating and intercooling are not illustrated in either of the closed cycles. However, they are equally applicable and for the same reasons as with the open cycle. The biggest single additional problem in the closed cycle is a practical method of building heat exchangers of large size for relatively high pressures and temperatures and small pressure drop. The problem is further complicated by the fact that the gases will carry foreign matter from combustion. These may both corrode and erode the exchanger and reduce the heat-transfer rate by depositing foreign material on the transfer surface.

### Gas-Turbine Control

Control of a combustion gas-turbine power unit can be simple and reliable, consisting only of control of the gas temperature by governing the rate of fuel supply. Governing control valves, as used with steam turbines, are avoided. Efficient partial-load control can be obtained by using two turbines in the same manner as shown in Fig. 12. One turbine drives a compressor at variable speed; the main or power turbine drives a generator at constant speed. Regenerators, reheaters, and intercoolers improve the full-load economy, and effect a marked improvement in the partial-load economy. In the closed cycle, by reducing the gas pressure as the load is reduced, practically the efficiency attained under full load can be maintained at partial loads.

### cessive Additions to Increase Efficiency or Size

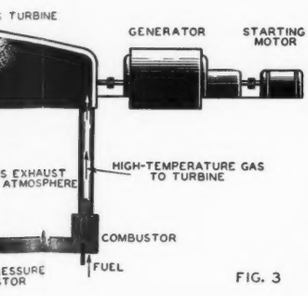
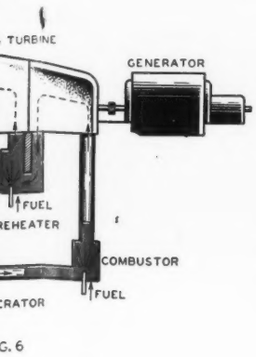



FIG. 3

**Fig. 6**—*Reheating some of the combustion gases after they have passed part way through the turbine improves the efficiency. The three principal efficiency-improving auxiliaries are a regenerator, an intercooler, and a reheater.*

**Fig. 7**—*In this Escher Wyss closed-cycle gas-turbine system, the products of combustion do not pass through the turbine. Their heat is transferred to a medium recirculated at high pressure through compressor and gas turbine.*

**Fig. 8**—*In this closed-cycle system, the combustor is a part of the compressor and turbine system, i.e., its internally fired cycle eliminates the gas heater of Fig. 7, but does entail the removal of solids from the system.*




G. 6

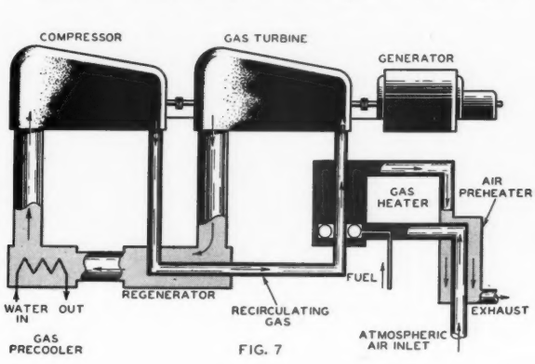



FIG. 7

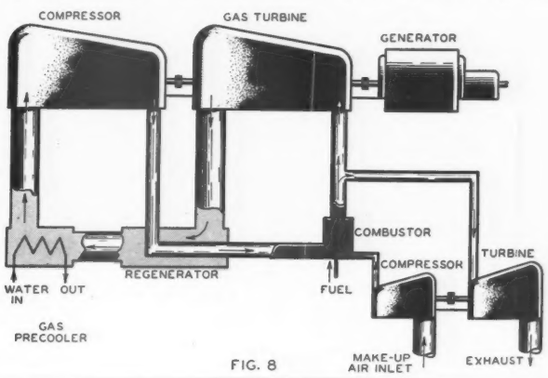



FIG. 8

TABLE I—COMPARISON OF COMBUSTION GAS TURBINE AND STEAM TURBINE, 5000 KW—3600 RPM

| | Open-Cycle Gas Turbine | | | Steam Turbine |
|---|---|---|---|---|
| | Simple Cycle | One reheat, one intercool, and regeneration | | Three Stages Feed-Water Heating |
| | Single Cylinder | High-Pressure Turbine | Low-Pressure Turbine | Single Cylinder |
| Inlet Pressure—lb per sq in. absolute | 88.2 | 100.4 | 39.4 | 465 |
| Inlet Temperature—degrees F total temperature | 1200 | 1200 | 1200 | 825 |
| Exhaust Pressure—lb per sq in. absolute | 14.7 | 39.4 | 15.1 | 3¼ |
| Steam or Gas rate—lb per kwhr. | 102 | 56 | | 10.5 |
| Full-Load Flow—lb per hour | 510 000 | 280 000 | | 52 500 |
| Inlet Volume Flow—cu ft per second | 990 | 475 | | 24.8 |
| Exhaust Volume Flow—cu ft per second | 3900 | 3250 | | 6120 |
| Ratio of Exhaust Volume to Inlet Volume | 3.95 | 6.85 | | 250 |
| Turbine Floor Area—sq ft | 160 | 150 | 155 | 100 |
| Net Generator Output—kw | 5000 | 5000 | | 5000 |
| Approximate Plant Thermal Efficiency—per cent | 18.4* | 29.4* | | 23.6 |

*Inlet Air Temperature 70 degrees F.

## Prewar Gas-Turbine Applications

In European countries, because of economic conditions, engineers have been avidly working on the gas-turbine principle. They attempted to develop it as soon as they had materials and compressors that even remotely offered a possibility of building successful units. The European installations are few in number and inferior in efficiency to what can now be built. They are, apparently, giving satisfactory results. Among the more interesting gas-turbine applications are the following:

A Brown-Boveri, 2200-hp combustion gas-turbine locomotive, operated by the Swiss Federal Railways.[1]

A 4000-kw gas turbine driving an electric generating set, and installed underground in a bomb-proof shelter as an emergency power supply, has been supplying the city of Neuchâtel, Switzerland with some electrical energy since the beginning of the war.

One of the earliest applications of the combustion gas turbine has been in connection with the Velox forced-circulation boiler.[3] The compressor supplies air to a boiler combustion chamber under approximately 35 pounds pressure, and the products of combustion from the boiler expanding through the gas turbine permit the turbine to drive the associated compressor.

Escher Wyss, a Swiss firm, have an industrial power plant using a closed-cycle gas turbine in which the products of combustion do not pass through the turbine.[4] They claim this cycle has an efficiency equal to that of an up-to-date steam power plant.

In the United States several gas turbines have been applied in connection with the processes for oil refining.[5] The compressor supplies air to burn carbon from the catalyst used in the cracking process, and the products of combustion (at a temperature below 1000 degrees F) expand through the gas turbine, which drives both a compressor and a generator.

The combustion gas turbine in connection with jet propulsion of airplanes has been discussed at length in English periodicals.[6] Of all applications, jet propulsion of airplanes is undoubtedly the most spectacular. Several countries are interested in this development, but the Italians are the only ones who have published information of actual results. In August, 1940, a successful flight was made in Italy with an aircraft using jet propulsion. The machine was driven solely by the reaction of the ejected gases. This machine, however, did not use a gas turbine. The exhaust gases of an aircraft engine that drove the compressor, and the gases from a combustor comprised the propelling jet.

## Gas-Turbine Applications

The possible applications of the gas turbine are numerous and important. In the simple open-cycle form for small capacities and the closed-cycle units for larger ratings, the device offers possibilities of competing with most types of engines and prime movers.

The simple open gas cycle requires no water. It has low weight and small space requirements combined with simplicity. With an efficiency of 20 per cent at 1200 degrees F, and the expected low maintenance of turbine apparatus it should prove a good locomotive drive. It possibly will offer strong

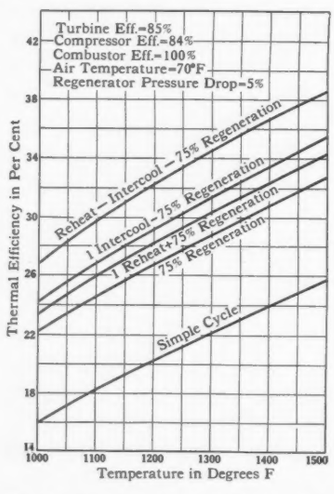



Fig. 9—*The thermal efficiency of the simple, open-cycle gas turbine compared with power units using different combinations of reheating, intercooling, and regeneration.*

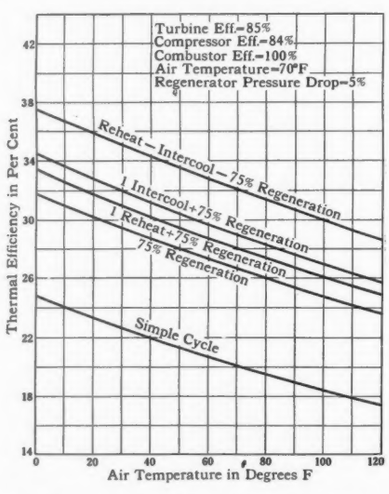



Fig. 10—*Temperature of the inlet air to the compressor has an important effect on overall efficiency. (A temperature of 1200 degrees F assumed at the turbine inlet.)*

competition to Diesel-powered locomotives. The inability of the gas turbine to operate in reverse makes either electric drive or the development of a satisfactory reversing gear necessary for locomotive application.

As a power plant for airplanes the gas turbine has real possibilities either for a propeller drive or for jet propulsion. For this service it will run at high speed to obtain maximum rating per unit weight of material.

For ship drives of moderate power, the combustion gas cycle offers efficiencies equal to the best modern marine steam power plants, which have maximum overall efficiencies of about 25 per cent. Weight and space requirements of equipment are a real factor in this application. The gas cycle eliminates the steam generator and steam condenser. The advantage in weight and space undoubtedly will favor the gas cycle, despite the gas compressor, the regenerator heat exchanger, and the large gas turbine. The requirement of astern operation in marine service handicaps the gas turbine except as an electric drive.

General application of the combustion gas cycle in the power-generation field will probably not take place until the problems of the use of coal are solved. The successful development of the closed cycle is necessary if units of very large capacity are to be built. The maximum capacity for which open-cycle units can be built will include most industrial applications. The open gas cycle may find early use for many special functions in the power-generation field, for example, for emergency standby service and on the ends of transmission lines. Here a simple, open gas cycle offers many advantages, such as low first cost, simplicity, small space requirements, and virtually automatic operation.

In the industrial field where both power and process steam are required the gas turbine also has possibilities, particularly where the steam required is relatively small in relation to the power load. This is different than the extraction steam turbine where large quantities of process steam per kilowatt are necessary to attain an efficient cycle. Here again, the use of coal as a fuel is necessary for a wide general application.

## The Job Ahead

Much is still to be done. Some of the publicity and many of the articles written on the combustion gas turbine have led some to believe that the gas turbine in all phases of its development and application is a solved problem, that with the end of hostilities, gas turbines will be produced for all types of applications. The impression may have been given that particularly high temperatures will soon be possible as a result of far-reaching metallurgical developments incurred by the war effort. In all fairness to the gas turbine, such a viewpoint should be avoided. It can lead only to disappointment and a feeling that the combustion gas turbine has failed to fulfill the expectations held for it.

One thing is certain, that the reduction of the gas turbine to practice will require the further expenditure of considerable time and money, both in the research laboratory and in the actual plant.

In a relatively short period designers have learned how to build gas turbines and axial-flow compressors for high efficiency. The research work done thus far indicates that this efficiency can be further improved. The job of doing this is tedious and costly. The proper type, arrangement and shape of blades to obtain this optimum efficiency require careful detail analysis of large numbers of possibilities in order to arrive at the best possible selection.

TABLE II—EFFECT OF DIFFERENT OPEN-CYCLE ARRANGEMENTS ON EACH MAJOR ELEMENT

| Item | Simple Cycle | Cycle with Regeneration | Intercool and Regenerate | Reheat and Regenerate | Intercool Reheat Regenerate |
|---|---|---|---|---|---|
| Figure No. | 3 | 4 | 5 | | 6 |
| Input in Fuel | 4.95 | 3.75 | 3.43 | 3.55 | 3.11 |
| Turbine Rating | 3.95 | 2.95 | 2.80 | 2.88 | 2.55 |
| Compressor Power | 2.95 | 1.95 | 1.80 | 1.88 | 1.55 |
| Useful Output | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| % Eff at 1200°F | 20.2 | 26.6 | 29.2 | 28.1 | 32.2 |
| Gas Temp. in °F at | | | | | |
| Turbine Inlet | 1 200 | 1 200 | 1 200 | 1 200 | 1 200 |
| Leaving Reheater | — | — | — | 1 200 | 1 200 |
| Turbine Exhaust | 635 | 790 | 695 | 920 | 865 |
| Leaving Regenerator | — | 455 | 350 | 560 | 520 |
| Air Temp. in °F at | | | | | |
| Compressor Inlet | 70 | 70 | 70 | 70 | 70 |
| Leaving Intercooler | — | — | 70 | — | — |
| Leaving Compressor | 490 | 340 | 230 | 440 | 405 |
| Entering Combustor | 490 | 680 | 575 | 800 | 750 |
| Press. lbs. per sq in. abs at | | | | | |
| Compressor Inlet | 14.7 | 14.7 | 14.7 | 14.7 | 14.7 |
| Compressor Discharge | 88.2 | 51.5 | 73.5 | 73.5 | 102.9 |
| Turbine Inlet | 88.2 | 50.2 | 71.7 | 71.7 | 100.4 |
| Turbine Exhaust | 14.7 | 15.1 | 15.1 | 15.1 | 15.1 |

Tabulation based on:

| | | | |
|---|---|---|---|
| Turbine Efficiency | 85% | Ambient Air Temp. | 70°F. |
| Compressor Efficiency | 84% | Regenerator Press. Drop | 5% |
| Combustor Efficiency | 100% | | |

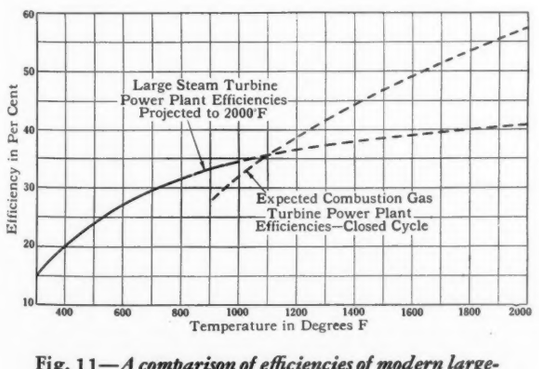



**Fig. 11**—*A comparison of efficiencies of modern large-size steam power plants with the expected best efficiencies of the closed-cycle gas-turbine plant. Whereas the efficiencies of steam plants vary widely with size, for the gas cycle, the efficiency is substantially constant.*

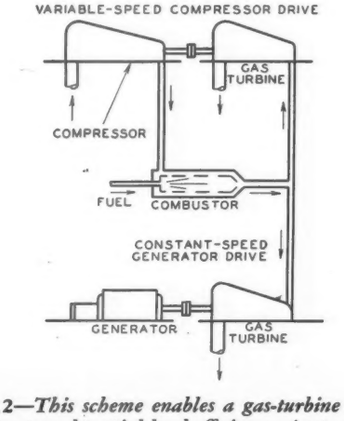



**Fig. 12**—*This scheme enables a gas-turbine unit to operate at good partial-load efficiency. A separate gas turbine drives the compressor at variable speeds. The main gas turbine can, therefore, drive the alternating-current generator at the necessarily constant speed.*

The axial-flow compressor now stands out as the natural choice of compressor because it can efficiently handle the large volume involved and it is small in physical size. Its partial-load performance characteristics, on the other hand, are far from ideal and will require extensive research.

To obtain materials suitable for operation at the higher temperatures which are so attractive, the metallurgists are looking at materials similar to the nonforgeable and nonmachinable tool steels. The method of forming these alloys to shape, such as precision casting to size, may revolutionize the methods of manufacture.

Combustors for operation with gas turbines have been developed for burning the high-grade fuel oils. Fundamentally the development to heavier grades of oil should offer no serious problems other than the time and money to carry out the necessary research. A far more difficult problem is the use of coal as a fuel. When using coal, the products of combustion will carry corrosive and erosive materials requiring removal.

The externally fired cycle, such as the Escher Wyss closed cycle, in which the products of combustion pass in heat exchange relation with the gas that expands in the turbine, offers a simpler solution of the coal problem. The heat exchanger here replaces the steam generator in the steam cycle. The rate of heat transfer in this heat exchanger will be low, as we are transferring heat from gas to gas, and the heat-transfer surface required will be large. To date, heat exchangers of the size required have never been built. Much of the industrial application of the gas turbine, especially those applications involving process steam, may hinge on the development of an economical heat exchanger of large size and one that is easy to manufacture.

At present research efforts are being expended in developments for national defense. In the postwar era, industry will have access to the developments in the gas-turbine field and to developments in high-temperature materials. These developments may considerably change present thinking. General applications of the gas cycle will have to wait until the postwar era. The gas-turbine art must advance beyond its present early development stages before it can be fully judged.

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## Turbine-Blade Growth Nurtured in Laboratory Hothouse

Turbine blades are not only stressed repeatedly, they undergo this stress at high temperature. It must be known that the blading metal can withstand this ordeal. To this end, fatigue-testing machines in the Westinghouse Research Laboratories stress the specimen 7200 cycles per minute at temperatures as high as 1500 degrees F. At these temperatures the fatigue curve does not flatten out after some 100 million cycles as when tested at room temperatures. Tests are, therefore, continued for about a month, or some 250 to 300 million cycles, in order to develop the characteristic of the curve which does not flatten out completely even at that number of stress cycles.

The alloy that withstands that fiery trial is shaped into blades which are themselves stressed at elevated temperatures. Here the root of the blade is fitted into a properly machined block that is held immovable. Two pieces of metal shaped to fit the contours of each side of the blade are pinned in place. To these blocks, affixed to the tip of the blade, is attached a yoke through which an alternating force is exerted at a frequency of about 500 cycles per minute. This is a constant-load fatigue machine, the stress being exerted through a heavy, calibrated spring that is alternately compressed and stretched by a cam-driven slide. In both testing devices, the specimens are heated by a bell-type furnace placed over the mounted test piece and constant temperature maintained by means of a differential expansion relay, the temperature being measured by a centrally located thermocouple.

*In this fatigue-testing machine, the blade is maintained at the desired temperature in the cubical furnace in the foreground. Mr. T. F. Hengstenberg is measuring the deflection of the calibrated spring which exerts the flexing force on the specimen through the yoke seen over the furnace. In the inset, the heated blade is mounted in the anchoring block and has the yoke fitting in place at the blade top.*

# Measuring Hydraulic Turbine Efficiency

*The electrical branch of engineering has been specially favored. The ability to make measurements of its quantities quickly and with a high degree of accuracy has been taken for granted by electrical men. While this good fortune is not enjoyed by all other branches of engineering, a description of one of the methods by which hydraulic engineers can accurately determine waterwheel efficiencies in a relatively short time will give electrical engineers a better understanding of some of the problems that confront their fellows.*

H. I. HOWELL
*Asst. to Vice President*
*Buffalo Niagara Electric Corp.*

THE GIBSON method of measuring the quantity of water flowing through a hydraulic turbine is based on a simple principle of physics. If the mass $M$ of a moving body is known, and if the average pressure $P$ required to bring it to rest in a known time $t$ can be measured, the velocity $v$ at the moment the pressure was first applied can be computed. This is Newton's second law of motion, sometimes known as the equation of impulse and momentum, which may be stated in the form $Mv=Pt$ or $v=Pt/M$. The measurement of the product of average pressure and time required to destroy the momentum in a given mass of fluid is precisely what is accomplished by the application of the Gibson method. The measurement is actually made by a photographic device, Figs. 1 and 2, that records the change in pressure and the time required to bring a known mass of fluid in motion to rest.

Actually, the camera records the movement of the top of a column of mercury in a glass U-tube. The glass-tube leg of the U-tube is connected by a small pipe, usually ¾ inch, to the conduit or penstock at a so-called piezometer section at a convenient downstream location. The other leg of the U-tube is similarly connected to the conduit at another piezometer section located some distance upstream from the first section. Hence, the height of the mercury is actually a measure of the difference in pressure between the two points at which the conduit is tapped, and this arrangement of apparatus is known as the differential application of the Gibson method.

The photographic record, of which a representative one is shown in Fig. 3, is made on a film 11 inches high by 18 inches long placed around a vertical cylinder that is slowly rotated during the test. In this way a record of pressure versus time is obtained just before, during, and after valve closure.

The distance between the two taps in the hydraulic conduit must be accurately known. This distance is specified by the ASME Power Test Codes for Hydraulic Prime Movers (1938) in terms of the conduit dimensions and water velocity. (The full-load velocity in feet per second times length of test section in feet must equal at least 200. Also, the test-section distance must not be less than 30 feet or less than twice the greatest dimension of the conduit cross section.)

Another arrangement of apparatus is known as the simple application of the Gibson method. In it only the glass-tube leg of the U-tube is connected to the conduit, the other being left open to atmospheric pressure. However, the differential application is the more convenient and is the one commonly used. The following description of the application and the derivation of the results will apply to that method.

The vertical motion of the top of the mercury column

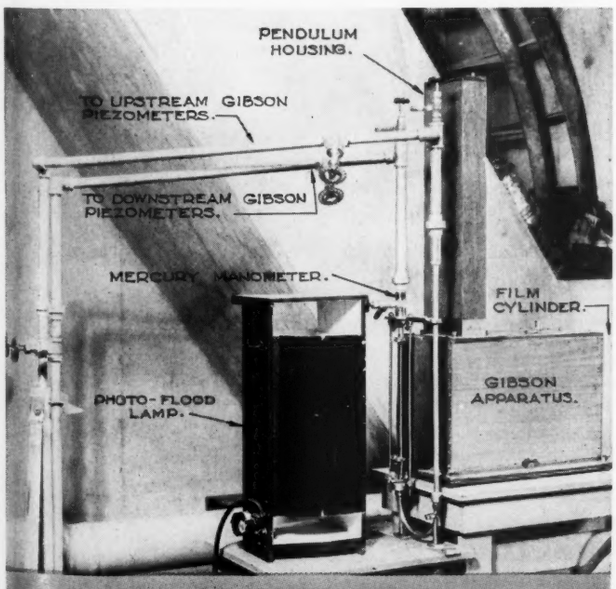



**Fig. 1**—*By the Gibson method of determining the efficiency of a hydraulic turbine, a photographic record is made of the variation in pressure between two sections of the penstock as the valves are closed. The pressure indications are brought to a U-tube containing a mercury column, which is photographed.*

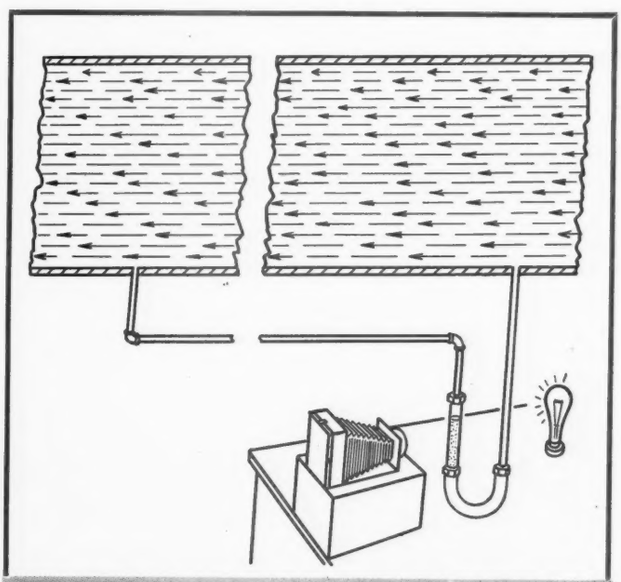


**Fig. 2**—*Diagrammatic view of Gibson method.*

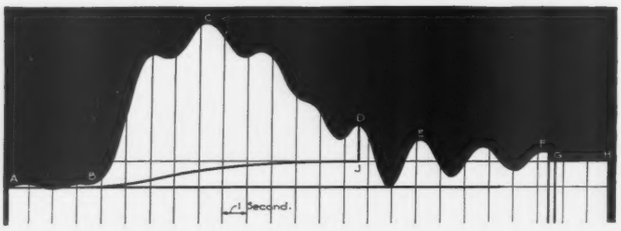



**Fig. 3**—*A typical photographic record of differential pressure in the penstock as valves are closed. From this, efficiency can be determined.*

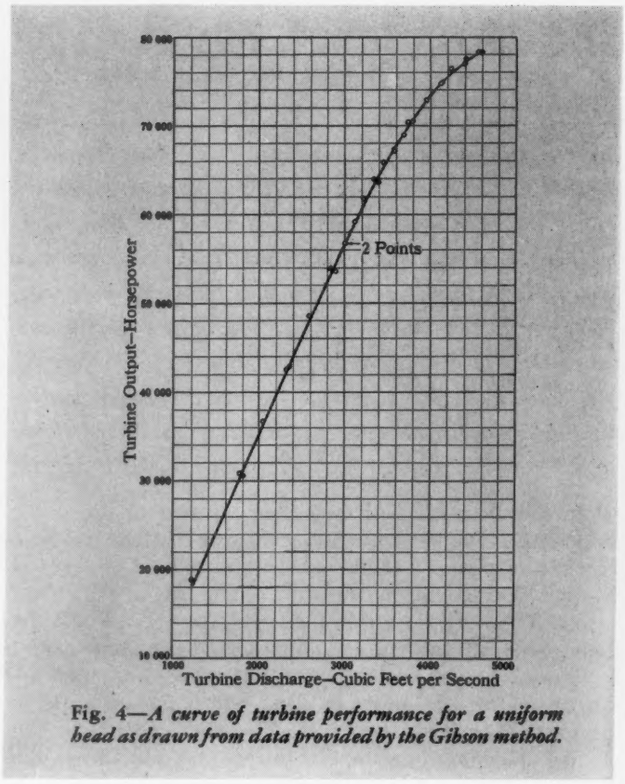



**Fig. 4**—*A curve of turbine performance for a uniform head as drawn from data provided by the Gibson method.*

obtained in the photographic record is caused by the differential pressure exerted in the two legs of the U-tube manometer connected to the Gibson apparatus. The horizontal distance between each of the vertical lines on the diagram, Fig. 3, represents one second of time. These lines are produced by a pendulum that blocks the light once each second as it swings past the lens. The location of the pendulum housing of the Gibson apparatus is shown in Fig. 1.

The exposure from *A* to *B*, called the running line of the diagram, shows the movement of the mercury column a few seconds before the turbine gates start to close. During this period, and for several minutes earlier, the turbine gates are held at a fixed gate opening as steadily as possible so that the flow of water through the turbine and the power output are relatively stable. About two minutes before the turbine gates start to close, observers measure the hydraulic head, servomotor piston stroke (inches of gate opening), and power output of the generator and other auxiliary equipment required to determine the power input to the generator shaft from the turbine.

At point *B*, the turbine gates start to close. The displacement of the mercury column along the wavy line *BCD* is caused by the change of pressure in the penstock between the upstream and downstream piezometer sections as the velocity of the water in the conduit is gradually destroyed. The instant the turbine gates reach the closed position (point *D*), the flow of water in the penstock ceases, except for the relatively small amount of water that leaks through the closed gates. Immediately after the turbine gates reach the closed position, the only forces acting on the mercury column are gravity and the dampening effect of friction in the hydraulic system between the two piezometer sections through the piping to the Gibson apparatus. This section of the diagram is commonly known as the afterwaves, and the mercury oscillates to a position of rest in a dampened harmonic wave motion (*DEF*).

The photographic record is continuous from *A* to *F*. The exposure of the film is interrupted at *F* after a few afterwaves have been photographed. As soon as the mercury column has come to rest (usually from one to two minutes after the gate closure), a photographic record is made of the top of the mercury column in that position (*GH*). This final record of the position of the mercury at rest is the so-called static line. The vertical distance between the average position of the running line (*AB* extended horizontally) and the static line *GH* represents a measure of the recovery of friction and velocity head in the conduit between the two piezometer sections as a result of the destruction of the velocity of the water.

The reversed curved line drawn between points *A* and *J* represents the gradual recovery of the friction and velocity head during the period of gate closure. The position of the line *AJ* is determined mathematically.[1]

The area (*BCDJB*) in square inches, measured by a precision planimeter, is the pressure-time area of the diagram, and represents a measure of the product of (a) the average pressure required to bring the mass of water in the test section of the penstock to rest and (b) the time in seconds the average pressure was applied. Hence the area is a measure of $Pt$ in the formula: $v = Pt/M$, where $v$ is velocity of the water in feet per second, $P$ is differential pressure in pounds, $t$ is time in seconds, and $M$ is total mass of water in pounds per foot per second.

The Gibson apparatus is calibrated in the laboratory to provide the values of its constants so that the area *BCDJB* in square inches is therefore readily translated into the product of average pressure expressed in feet of water and time in seconds. Hence, having thus measured the value of $Pt$ and knowing the mass of the water in the test section of the con-

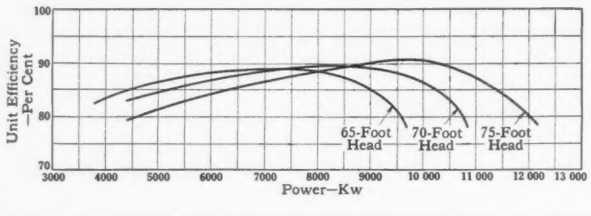
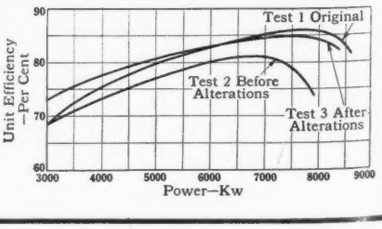
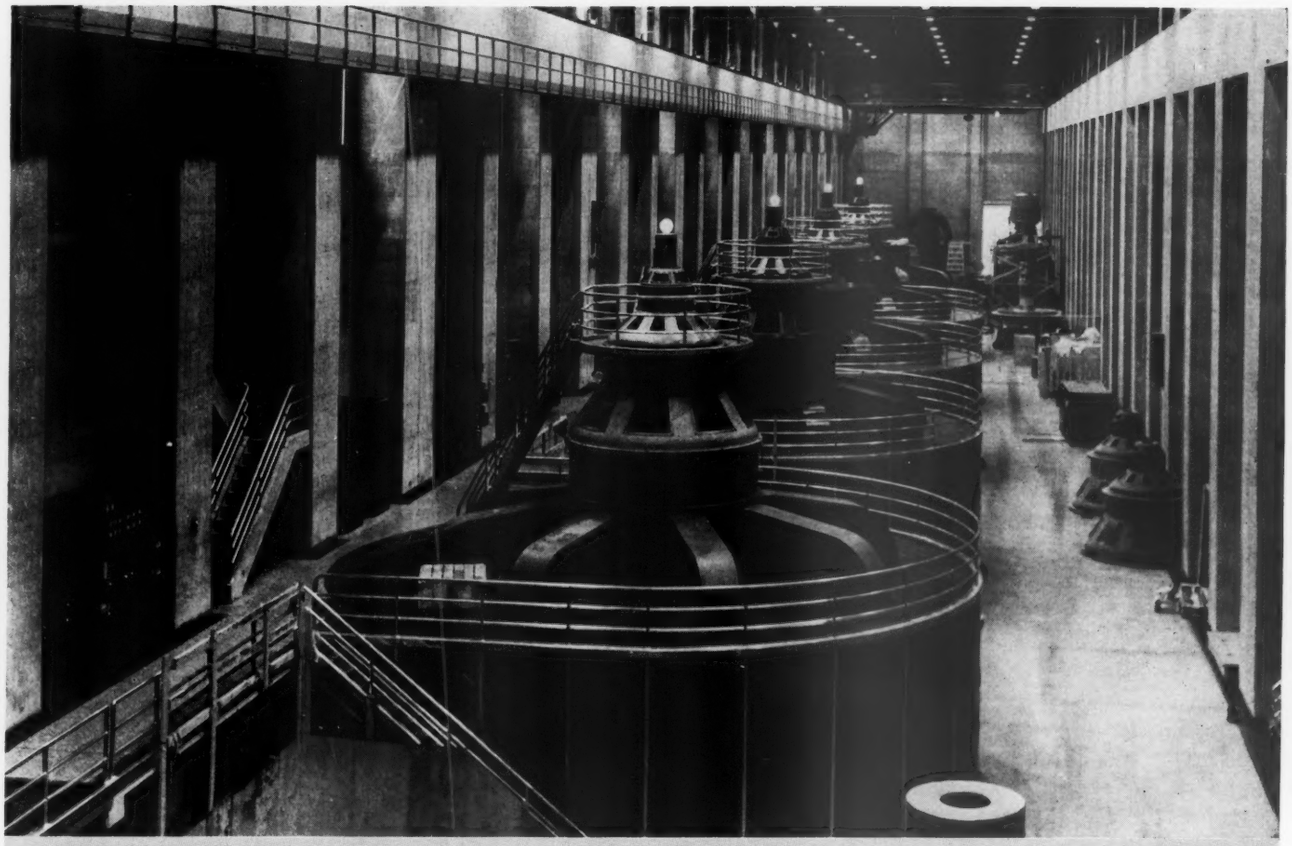



**Fig. 5**—*Performance of a waterwheel turbine under three heads.*

**Fig. 6**—*Data obtained from actual tests frequently make turbine improvements possible.*





*The hydraulic performance of the 82 500-kw turbines at Boulder Dam has been analyzed by the Gibson method.*

duit, the average velocity of the water in the conduit at the instant the turbine gates started to close may be computed. The quantity of water $Q$ in cubic feet per second flowing at that instant is equal to the average cross-sectional area of the test section of the conduit in square feet multiplied by the average velocity in feet per second, or $Q=Av$.

Some water always leaks past the closed turbine gates. Because the velocity of the leakage water in the conduit is not destroyed by the gate closure, this quantity is not measured on the Gibson diagram. It is, therefore, necessary to make a separate measurement of the turbine-gate leakage. The total quantity of water flowing in the conduit at the instant the turbine gates start to close is the sum of the quantity derived from the Gibson diagram and the quantity of leakage water.

### The Test Points and the Time Required to Make Them

A complete test on a hydroelectric unit usually consists of from 25 to 30 individual runs, made at various amounts of turbine-gate opening from as low as about 15 or 20 per cent opening to full gate opening. During each test run, the gate opening, head, and power output are measured and when these observations have been completed, the gates are gradually closed to obtain the Gibson diagram.

The ASME Power Test Code for Hydraulic Prime Movers requires that within the guarantee range, at least three sets of observations shall be made at each of seven gate openings. It is common, however, by mutual agreement between the manufacturer and the purchaser prior to the acceptance test, to spread the 21 or more test points throughout the guarantee range to better advantage. The points for a representative Gibson test are plotted in Fig. 4. The distribution of the test points is such that the position of the curve is definitely established throughout the complete range of gate openings used during the test.

In general, the field work for the test of one hydraulic unit in a station, including the time required to inspect the turbine and piezometers and to set up and connect the Gibson apparatus to the conduit, install current and potential test transformers, meters, head gauges, etc., and the completion of from 25 to 30 runs, requires from four to five days. The actual running of the test after the electrical and hydraulic equipment has once been set up usually requires from eight to twelve hours. Where more than one unit is to be tested in a powerhouse, the field work required to test the additional units is about three days per unit. After the field work has been completed, about five or six days per unit are required to compute the results from the test data.

### What the Tests Accomplish

Gibson tests on more than two hundred hydroelectric units in this country have been made in many instances to determine whether or not the turbine has the guaranteed efficiencies. In addition to acceptance tests, many machines have been checked to determine the operating characteristics of the units under various conditions. For example, in some plants tests have been made on the same unit under different operating heads, as in Fig. 5, to determine the effect of variation in head on the efficiency and operating characteristics of the unit. The effect of variation in head can be estimated from results of model tests, but under certain circumstances, operators prefer to make actual tests on the prototypes.

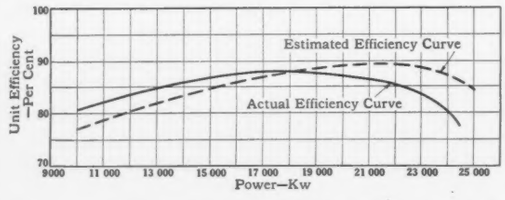



**Fig. 7**—*A Gibson test makes possible a comparison of actual turbine performance with that expected by the designers. In this case, before the test was made the calculated curve was used as the basis of operation. A gain of 2.5 per cent in efficiency is obtained if the waterwheel is operated at 17 500 kw instead of 21 500 kw.*

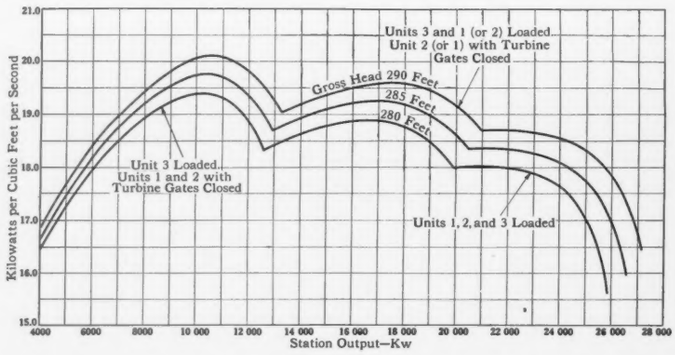

Kilowatts per Cubic Feet per Second
Units 3 and 1 (or 2) Loaded
Unit 2 (or 1) with Turbine Gates Closed
Gross Head 290 Feet
285 Feet
280 Feet
Unit 3 Loaded
Units 1 and 2 with Turbine Gates Closed
Units 1, 2, and 3 Loaded
Station Output—Kw

**Fig. 8**—*Knowledge of actual turbine performance under different conditions enables the load dispatcher to utilize his various units most effectively.*

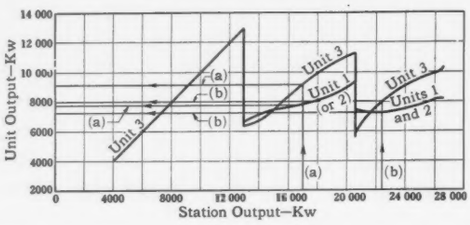



**Fig. 9**—*Test data can be made the basis for load dispatching. (a) For station load of 17 000 kw, follow vertical line from this point to points of intersection on curves. From these points follow horizontal lines to unit output scale to determine load on each unit; for example, unit 3, 9150 kw, unit 1 (or 2) 7850 kw. (b) For station load of 22 600 kw, proceed as in (a). Unit output figures are as follows: unit 3, 8000 kw, units 1 and 2, 7200 kw each.*

Tests have been conducted on units to determine the effect of alterations that have been made to the turbine. Examples of the results obtained from such tests are shown in Fig. 6. The importance of making an actual field test on a unit to determine its actual performance instead of estimating its operating characteristics is shown in Fig. 7.

One of the most beneficial results that can be obtained from a complete field test of a hydroelectric development relates to the determination of the division of load among the various units in the powerhouse to obtain the most efficient use of the available water. A diagram of the preferred loading schedule for three units in a powerhouse, computed from the results of a complete field test at the station, is given in Fig. 8.

The diagram shows that the most efficient use of water by the station is obtained when unit 3 (10 000 kw) is operated and the turbine gates of the other two units are closed. For a gross head of 285 feet, the maximum efficiency in terms of kilowatts per cubic foot per second is 19.77 when unit 3 is operating alone and the station output is 10 500 kw. The division of load for best use of water is shown in Fig. 9, the determination of which has been described elsewhere. [2, 3]

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2—"Operating a Hydroelectric System for Best Economy and Means Employed for Checking Performance of Operation," *Nela Bulletin*, December, 1929.

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## The Background of the Gibson Method of Measuring Water Flow

About 1920 a new method of measuring water flow was developed by Norman R. Gibson, who was at that time hydraulic engineer, Niagara Falls Power Co. After its accuracy had been verified by careful laboratory checks, it was first used as a means of testing the hydraulic turbines at Niagara Falls. But since that time it has become rather generally accepted as an accurate, convenient, and economical method of measuring water flow in hydroelectric installations. The method has been used to determine the operating performance and characteristics of more than two hundred hydroelectric units, including some of the largest Bureau of Reclamation units such as those at Boulder Dam and Grand Coulee. The method has also been used to conduct tests in Canada, Russia, Germany, Italy, Japan, and South America. The tests in this country have been made on low- and high-head plants. The turbines have been equipped with runners of various types such as fixed- and adjustable-blade propellers, Francis and Fourneyron reaction wheels, and impulse wheels. Some units have been installed with a vertical shaft setting and others with a horizontal setting. Some units have been in service for more than forty years. Mechanisms of antiquated design as well as the most modern governing equipment have been used to control the turbine gates, which have been of both the wicket and cylinder types.

Water has been supplied to the turbines by closed conduits constructed of steel, concrete, or wood-stave pipes of various lengths from short penstocks to long pipe lines.

The measured quantity of water discharged by the turbines has varied from about five cubic feet per second in some cases to 9000 cubic feet per second in others.

The factors that determine whether or not the Gibson method of testing can be applied to a particular hydroelectric development are not related to the magnitude of the head, the type of turbine runner and turbine gates, or the quantity of water discharged by the turbine. The important factors are the physical limitations of the closed conduit used to supply water to the turbine and the ability to shut off the water at the turbine at a relatively continuous rate of closure in a short period of time by some type of gate mechanism. In general a satisfactory test can be made if the time required to close the gates from their wide-open position is about 10 to 20 seconds, although satisfactory results have been obtained in a test on an impulse turbine where the needle-valve closing time was as much as two minutes.

Photo courtesy Army Air Forces

# Happy Landings—Aided by Instruments

***Engineers are closing in on the most important remaining hazard to safe flying—landing when the ground can't be seen. Radio and instrument engineers have combined to provide a blind-landing system by which the airplane pilot watches the two crossed pointers of an instrument instead of the ground. This system, although possibly not the ultimate, is being used successfully and extensively in both commercial and military service.***

THOUSANDS of airplanes, mostly military, some commercial, are now being landed when the visibility ceiling is 100 feet or less. Five years ago (except for a few experimental installations) landings could not be made with ceilings lower than 400 feet. The significance of this is that, with the new apparatus, about 90 per cent of these landings can be made with ceilings as low as 100 feet. In fact many perfect landings have been made with the pilot unable to see his wing tips.

### How Instrument Landing Works

To provide the pilot with guidance in both horizontal and vertical planes, four separate radio-transmitting stations are located on or near the airport. The one that furnishes the homing path is called the localizer. It is basically a two-course radio beam established at an ultra-high frequency. Essentially, this is created by using two sharply directional antenna systems that set up two loops, back to back so to speak, as shown in Fig. 1. One is modulated at, say 150 cycles, the other at 90 cycles.

The plane is equipped with suitable radio receivers, the outputs of which are delivered to an instrument of the cross-pointer type. This is comprised of two sensitive d-c milliammeters combined into a single case. One element—the one responsive to the localizer or "on-course" beam—actuates a vertical pointer. The second element—the one that is indicative of position above or below the proper glide path—operates a horizontal pointer.

While the airplane is still some distance from the airport, the special radio set compares the strength of the signals from the two localizer loops. If they are almost equal the airplane is on course. This fact is registered by the vertical pointer remaining in a vertical position. Should the plane be to the right or left of the course, one of the two received localizer signals predominates, causing the vertical of the crossed pointers to swing to the right or left, and by an amount roughly proportional to the amount of deviation from course. The sharpness of the course beam is largely a matter of design and is usually a compromise of several factors. The beam has been about three degrees in width.

Vertical guidance as the airport is approached is provided by three transmitters. One of these establishes the glide path, the other two are markers. The markers are simply radio beams transmitted vertically and serve as reference points for the pilot. One marker is usually located some four to five miles from the airport. When the plane crosses this upward-projected outer marker beam, the signal is picked up by a marker receiver, which lights a lamp before the pilot. The pilot should fly his ship so that he is about 1500 feet above the ground when he crosses this outer marker, to be ready to assume the angle of glide to the landing field.

A similar vertical marker is established at the boundary of the landing field. Crossing this beam also lights a lamp on the instrument board, indicating to the pilot that he has reached the edge of the field. A third or intermediate marker is sometimes placed between the outer and boundary markers.

The glide-path transmitter, located near the end of the runway, sends out over an array of special antennas several radio loops, somewhat as shown in Fig. 2. The glide-path receiver in the airplane compares the strengths of the two loops and delivers its findings to the horizontal pointer of the cross-pointer instrument. The pilot, after receiving the lamp indication from the outer marker, flys the ship to keep the horizontal pointer horizontal, which assures him that the plane is following the invisible radio-established glide path and that he will touch his wheels to earth at the end of the runway without visual reference to the ground.

*The intersection of the two crossed pointers indicates to the pilot, as he brings his plane in to a landing, whether he is above or below, to the right or to the left of the correct landing position.*

### The System Has a Long History

The history of experiments with instrument landing dates back many years, to at least 1919 when the National Bureau of Standards developed experimentally a radio system to aid airplane landing during poor visibility. There have been many schemes and many experimenters. The present scheme, which has emerged as the most successful, is old. The famous Jimmy Doolittle, in 1929, made the first successful instrument landing at Mitchell Field. The field had been equipped by the Bureau of Standards for the Aeronautics Branch of the Department of Commerce with an experimental apparatus using 300 kc, in which the principles were substantially the same as those of today. However, the embodiment of those principles into apparatus that is completely reliable, consistent, and that commands confidence of the pilots, has been a slow and tedious process.

Work was done by the Army Air Corps at Wright Field at Dayton, by the Washington (D.C.) Institute of Technology, by the Transcontinental and Western Air Lines, Inc. at Kansas City, by the Bureau of Air Commerce (now the Civil Aeronautics Authority), by the Lorenz Company of Germany, by the International Telephone and Telegraph Company, by Bendix Corp., by United Air Lines, and others.

In 1937 a coordinating committee made up of representatives of manufacturers, airlines, and government agencies drew up specifications based on all the work done up until that time for an instrument-landing system. An experimental installation of equipment built to these standards was made at Indianapolis airport in October 1939 by International Telephone and Telegraph. A number of commercial transport planes were equipped for this system and over a hundred airline pilots trained to use it. The results, on the whole, were satisfactory, so much so that plans were made to equip the leading 100 airports of the United States with an improved version of the Indianapolis equipment. This program would have been completed long ago had not the war interfered with radio and instrument manufacture. However, it is still on the books and is being gradually completed.

At Indianapolis and several other commercial airports, and on dozens of Army and Navy landing fields, this system is in daily use. Landings have been repeatedly and consistently made on spots no larger than fifty feet by the use of the instrument system alone. However, perfection can by no means be claimed for the system. There has been a host of difficult problems, such as interference by local structures and by storms, matters of best antenna arrangement, and placement, etc. Choice of frequencies has required much experiment, and to this end the concurrent developments in ultra-high frequencies have been enormously helpful, in fact have been the key to the present degree of success of the system. The shape of the glide path—whether it should be straight or parabolic, or a combination of the two—has received much consideration by both radio men and pilots. The matter is still not wholly settled, in fact the glide-path requirements of various types of planes (particularly within the military classification) are different. These differences in glide path are matters of radio detail, not of essential principle in radio apparatus. Radio engineers are now able to "throw" almost any type of curve that airplane operators decide is required.

There are problems yet to be solved, but the system works and works well. There is no assurance that some completely different system will not be found superior. In any case it marks a long forward step toward achievement of safe landings of airplanes when visibility is poor.

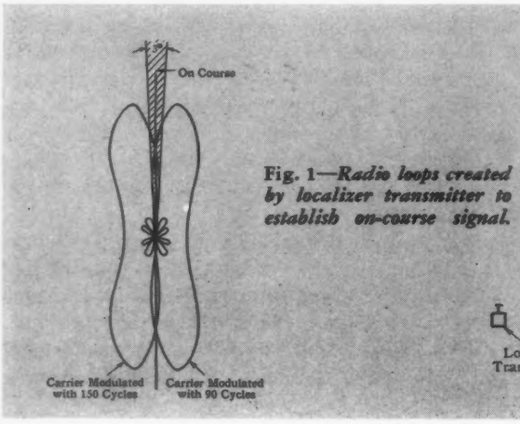
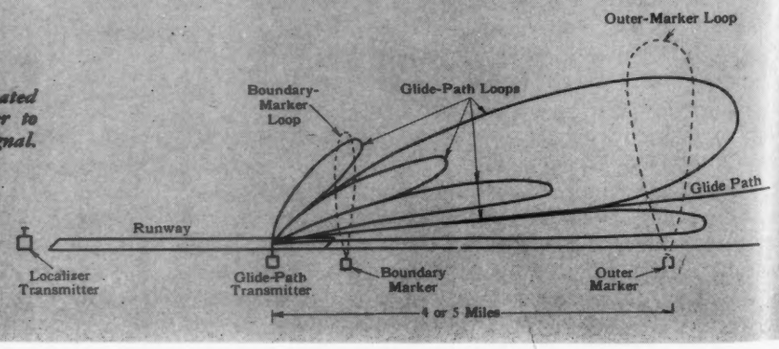



**Fig. 1**—*Radio loops created by localizer transmitter to establish on-course signal.*

**Fig. 2**—*Location of transmitters for instrument landing of airplanes.*



# Unbalanced Voltage and Wound-Rotor Motors

*The quest to obtain with induction motors the speed performance of direct-current motors is endless. One method seldom considered is to unbalance the primary voltage. The theory of this interesting possibility and the resulting performance for different amounts of voltage unbalance and rotor resistance are considered without reference to the possible applications of the scheme.*

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*Industrial Motor Engineer*
*Westinghouse Electric & Mfg. Co.*

THE DESIRABLE speed-torque characteristics of d-c motors can also be obtained with wound-rotor induction motors if we are willing to unbalance the voltages to the motor primary. It is frequently forgotten that one way to cause an induction motor to run at considerably less than synchronous speed at no-load is to apply an unbalanced voltage to its stator terminals.

Consider a wound-rotor motor having normal speed-torque characteristics as shown in Fig. 1. With the secondary short circuited, this machine has a pull-out torque equal to 275 per cent and a starting torque equal to 150 per cent of rated full-load torque. The other curves are those for different amounts of external secondary resistances, the resistances chosen being such as to provide 2, 4, 5, 6, and 8 times the secondary resistance of the motor when the secondary is short circuited. These resistances will be referred to as $2\times R_2$, $4\times R_2$, etc.

The connections used to unbalance the primary voltage on this hypothetical motor are shown in Fig. 2. Two of the three 220-volt line leads are attached to the 0- and 220-volt taps of an autotransformer, and the third line lead is connected directly to motor lead $T_3$. Motor lead $T_2$ is connected to the 260-volt tap on the autotransformer, and motor lead $T_1$ is connected to different taps on the autotransformer. Four conditions of unbalance will be considered: $T_1$ connected successively to four taps—240, 220, 160, and 110 volts—on the autotransformer. An analysis of the vector representations of the unbalanced primary voltages reveals that for the four conditions of unbalance, the potentials across the motor terminals are as shown in table I.

To explain how an induction motor runs at less than synchronous speed at no-load by reason of applying an unbalanced primary voltage, it is necessary to consider the fundamentals of symmetrical components. A prime theorem of symmetrical components is that any unbalanced system of three-phase voltages can be broken down into three balanced components, one of positive sequence, one of negative sequence, and one of zero sequence. The latter has no significance here. Hence, the unbalanced primary voltage on the hypothetical motor can be considered as two independent balanced voltages, one producing a rotating field in a positive direction, and the other producing a rotating field in the negative direction. Thus, at a given slip, the torque of an induction motor with an unbalanced primary voltage is the torque produced at that slip of a balanced voltage equal to the positive sequence, less the torque at the same slip produced by a balanced voltage equal to the negative sequence. The positive- and negative-sequence voltages caused by the four conditions of primary voltage unbalance listed in the preceding paragraph, calculated by means of their symmetrical components, are summarized in table II. The corresponding torques, at various slips, produced by the positive- and negative-sequence voltages of table II, were calculated for the different amounts of secondary resistance, and the resultant torques obtained at these slips are recorded in table III. As an example, these torques are calculated for 75 per cent synchronous speed with $2\times R_2$ secondary resistance. Referring to the $2\times R_2$ curve in Fig. 1, 220 volts (balanced) applied across the stator terminals, the torque at 75 per cent synchronous speed is 195 per cent positive sequence, and 175 per cent negative sequence. From table II for lead $T_1$ on 240-volt tap, the positive-sequence voltage is 143 and the negative sequence 130 volts. Torque varies as the square of the applied voltage; the torque produced by the positive-sequence field is $(143/220)^2\times 0.95\times 195$ per cent $= 78$ per

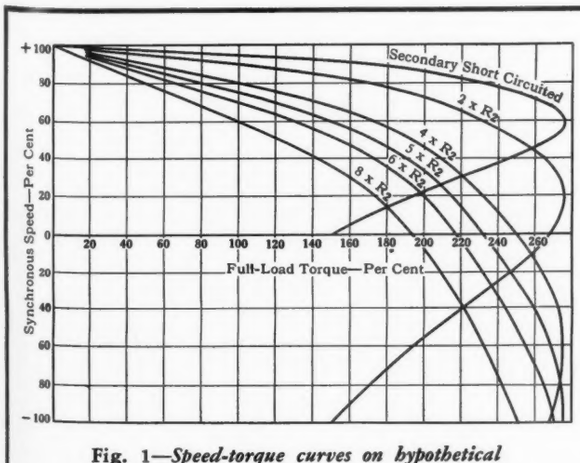



**Fig. 1**—*Speed-torque curves on hypothetical motor with normal balanced primary voltage.*

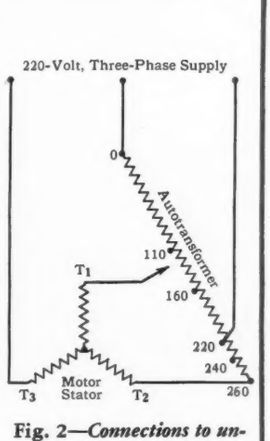



**Fig. 2**—*Connections to unbalance primary voltage.*

TABLE I—MOTOR LINE VOLTAGE FOR DIFFERENT AUTOTRANSFORMER VOLTAGES

| Tap for $T_1$ | Motor Line Volts | | |
|---|---|---|---|
| | $T_1-T_2$ | $T_2-T_3$ | $T_1-T_3$ |
| 240 | 20 | 242.5 | 231 |
| 220 | 40 | 242.5 | 220 |
| 160 | 100 | 242.5 | 198 |
| 110 | 150 | 242.5 | 190.5 |

TABLE II—POSITIVE- AND NEGATIVE-SEQUENCE MOTOR LINE VOLTS FOR DIFFERENT UNBALANCED VOLTAGES

| Tap for $T_1$ | Positive Sequence | Negative Sequence |
|---|---|---|
| 240 | 143 | 130 |
| 220 | 151 | 116 |
| 160 | 170 | 85.3 |
| 110 | 190 | 55.7 |

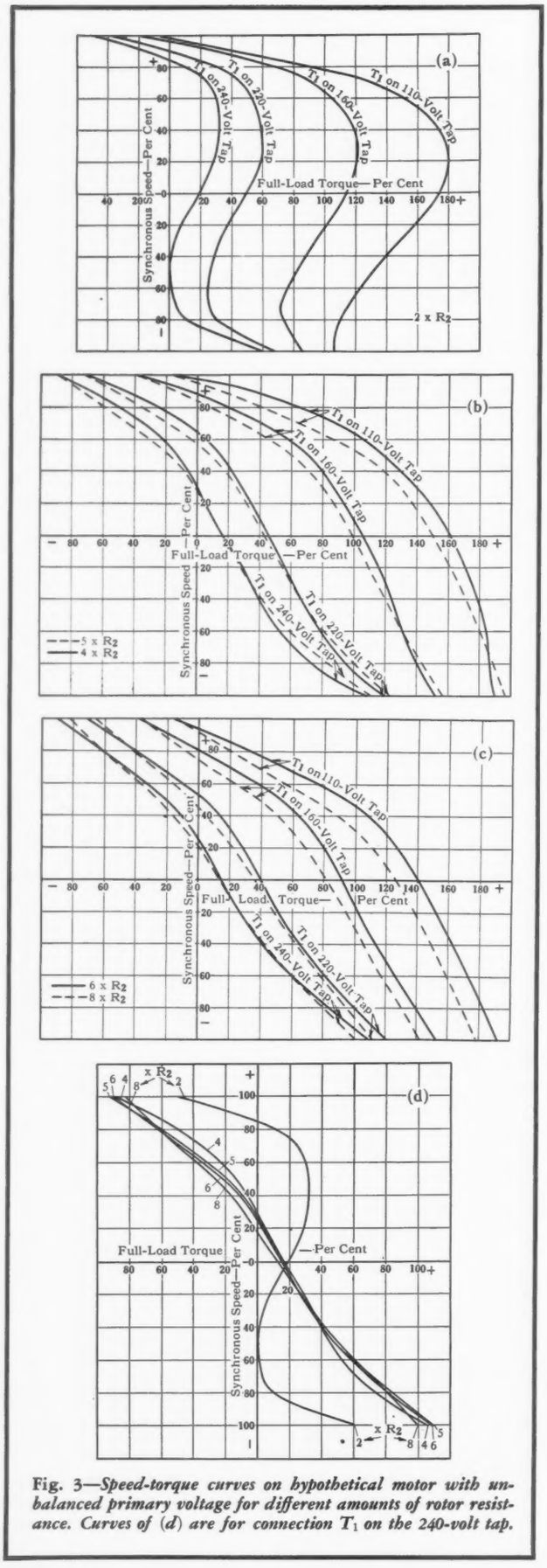



**Fig. 3**—*Speed-torque curves on hypothetical motor with unbalanced primary voltage for different amounts of rotor resistance. Curves of (d) are for connection $T_1$ on the 240-volt tap.*

cent; and for the negative sequence field $\left(\frac{130}{220}\right)^2 \times 0.95 \times 175$ per cent = 58 per cent. (The 0.95 in the above equations is an arbitrary saturation factor used in making all torque calculations.) The resultant torque is then 78 − 58, or 20 per cent. In like manner the other figures of table III were obtained and the results plotted as the speed-torque curves of Figs. 3 (a), (b), (c), and (d). Figures 3 (a), (b), and (c) show how the speed-torque curves for a given secondary resistance vary under different amounts of primary-voltage unbalance. Figure 3(d) shows how the speed-torque curves for a given amount of primary voltage unbalance vary with different values of secondary resistance.

These speed-torque curves show that one of the objectives, a no-load speed less than synchronous speed, has been attained. Further, as the secondary resistance is increased, the curves cross the zero-torque axis at lower speed values.

The answer to the problem might seem to be simply to increase the secondary resistance even more, thus lowering the speed at zero torque still further. This would be true if the torques were not also lowered. In order to obtain good speed regulation it is desirable for the speed-torque curve to be as flat as possible, because if it is not, a slight change in load results in a large change in speed. According to Fig. 3 (d), as the secondary resistance is increased from $2 \times R_2$ through $5 \times R_2$, the torque at synchronous speed increases from −50 per cent to −91 per cent, while the speed at zero torque decreases from 84 per cent to 26 per cent of synchronous. However, when the secondary resistance is increased to 6 or $8 \times R_2$, although the speed at zero torque comes down a little more, the torque at synchronous speed reduces from −91 to −90 per cent (at $6 \times R_2$) and −83 (at $8 \times R_2$). Thus, for a secondary resistance of $8 \times R_2$, the speed-torque curve is assuming a steeper slope, which is undesirable from the speed-regulation standpoint. Hence, an optimum value of secondary resistance is realized for best operational characteristics, in the case of this hypothetical motor about $5 \times R_2$. This is the value of secondary resistance, shown by Fig. 1, that brings the pull-out torque down to −100 per cent synchronous speed.

Speed-torque curves of the same general characteristics as those shown here can be obtained by unbalancing the primary voltage in any manner feasible. Also, this same theory could be applied to squirrel-cage induction motors.

### Experimental Results of Primary-Voltage Unbalance

To check the accuracy of the preceding calculated speed-torque curves with the primary voltage unbalanced, an actual motor was tested with unbalanced primary voltage. The motor tested was a 2-hp, 4-pole, 3-phase, 60-cycle, 220-volt, wound-rotor induction motor. First, the slip at pull-out on this motor was determined, and hence the amount of external secondary resistance required to bring the pull-out point down to −1800 rpm. Then, with this optimum value of secondary resistance, a speed-torque curve was taken from +1800 rpm to −1800 rpm with normal balanced voltage applied to the stator winding. This speed-torque curve is shown in Fig. 4.

Next, the primary voltage was unbalanced by means of the connections shown in Fig. 2, and three speed-torque curves taken, one each with lead $T_1$ on the 220-, 160-, and 110-volt taps. In each of these three speed-torque curves, the optimum value of secondary resistance was used. The actual test data for the three conditions of unbalanced primary voltage is recorded in table IV, and from this data the test speed-

TABLE III—CALCULATED TORQUES FOR HYPOTHETICAL MOTOR WITH UNBALANCED PRIMARY VOLTAGE

| Syn. Speed Per Cent | Torques in Percent of Full Load | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_1$ on 240 V Tap | | | $T_1$ on 220 V Tap | | | $T_1$ on 160 V Tap | | | $T_1$ on 110 V Tap | | | |
| | Pos. Seq. | Neg. Seq. | Res. | Pos. Seq. | Neg. Seq. | Res. | Pos. Seq. | Neg. Seq. | Res. | Pos. Seq. | Neg. Seq. | Res. | |
| 100 | 0 | 50 | −50 | 0 | 40 | −40 | 0 | 21 | −21 | 0 | 9 | −9 | |
| 75 | 78 | 58 | 20 | 87 | 46 | 41 | 110 | 25 | 85 | 138 | 11 | 127 | |
| 50 | 100 | 68 | 32 | 112 | 55 | 57 | 142 | 29 | 113 | 177 | 13 | 164 | |
| 25 | 110 | 80 | 30 | 123 | 63 | 60 | 156 | 34 | 122 | 195 | 15 | 180 | |
| 0 | 108 | 89 | 19 | 120 | 71 | 49 | 152 | 38 | 114 | 190 | 16 | 174 | |
| −25 | 96 | 91 | 5 | 107 | 73 | 34 | 136 | 39 | 97 | 170 | 17 | 153 | |
| −50 | 83 | 83 | 0 | 92 | 66 | 26 | 117 | 36 | 81 | 146 | 15 | 131 | |
| −75 | 70 | 65 | 5 | 78 | 52 | 26 | 99 | 28 | 71 | 124 | 12 | 112 | |
| −100 | 60 | 0 | 60 | 67 | 0 | 67 | 85 | 0 | 85 | 106 | 0 | 106 | $2\times R_2$ |
| 100 | 0 | 89 | −89 | 0 | 71 | −71 | 0 | 38 | −38 | 0 | 16 | −16 | |
| 75 | 50 | 91 | −41 | 56 | 72 | −16 | 71 | 39 | 32 | 89 | 17 | 72 | |
| 50 | 78 | 91 | −13 | 87 | 72 | 15 | 110 | 39 | 71 | 132 | 17 | 115 | |
| 25 | 91 | 88 | 3 | 101 | 70 | 31 | 128 | 38 | 90 | 160 | 16 | 146 | |
| 0 | 100 | 83 | 17 | 112 | 66 | 46 | 142 | 36 | 106 | 177 | 15 | 162 | |
| −25 | 107 | 75 | 32 | 119 | 60 | 59 | 151 | 32 | 119 | 188 | 14 | 174 | |
| −50 | 110 | 64 | 46 | 123 | 51 | 72 | 155 | 28 | 127 | 194 | 12 | 182 | |
| −75 | 110 | 42 | 68 | 123 | 33 | 90 | 155 | 18 | 137 | 194 | 8 | 186 | |
| −100 | 107 | 0 | 107 | 120 | 0 | 120 | 152 | 0 | 152 | 189 | 0 | 189 | $4\times R_2$ |
| 100 | 0 | 91 | −91 | 0 | 73 | −73 | 0 | 39 | −39 | 0 | 17 | −17 | |
| 75 | 40 | 91 | −51 | 45 | 72 | −27 | 57 | 39 | 18 | 71 | 17 | 54 | |
| 50 | 70 | 88 | −18 | 78 | 70 | 8 | 98 | 38 | 60 | 122 | 16 | 106 | |
| 25 | 84 | 83 | 1 | 94 | 66 | 28 | 119 | 36 | 83 | 149 | 15 | 134 | |
| 0 | 93 | 77 | 16 | 104 | 61 | 43 | 132 | 33 | 99 | 164 | 14 | 150 | |
| −25 | 100 | 70 | 30 | 112 | 55 | 57 | 142 | 30 | 112 | 177 | 13 | 164 | |
| −50 | 106 | 57 | 49 | 118 | 46 | 72 | 150 | 25 | 125 | 187 | 11 | 176 | |
| −75 | 110 | 33 | 77 | 122 | 26 | 96 | 155 | 14 | 141 | 193 | 6 | 187 | |
| −100 | 110 | 0 | 110 | 123 | 0 | 123 | 156 | 0 | 156 | 195 | 0 | 195 | $5\times R_2$ |
| 100 | 0 | 90 | −90 | 0 | 71 | −71 | 0 | 38 | −38 | 0 | 16 | −16 | |
| 75 | 34 | 88 | −54 | 38 | 70 | −32 | 48 | 37 | 11 | 60 | 16 | 44 | |
| 50 | 62 | 83 | −21 | 69 | 66 | 3 | 87 | 35 | 52 | 108 | 15 | 93 | |
| 25 | 78 | 78 | 0 | 87 | 62 | 25 | 110 | 33 | 77 | 138 | 14 | 124 | |
| 0 | 87 | 72 | 15 | 97 | 57 | 40 | 123 | 31 | 92 | 154 | 13 | 141 | |
| −25 | 95 | 65 | 30 | 105 | 51 | 54 | 133 | 28 | 105 | 167 | 12 | 155 | |
| −50 | 100 | 51 | 49 | 112 | 40 | 72 | 141 | 22 | 119 | 177 | 9 | 168 | |
| −75 | 106 | 28 | 78 | 118 | 22 | 96 | 149 | 12 | 137 | 186 | 5 | 181 | |
| −100 | 109 | 0 | 109 | 121 | 0 | 121 | 153 | 0 | 153 | 191 | 0 | 191 | $6\times R_2$ |
| 100 | 0 | 83 | −83 | 0 | 66 | −66 | 0 | 36 | −36 | 0 | 15 | −15 | |
| 75 | 25 | 80 | −55 | 27 | 63 | −36 | 35 | 34 | 1 | 43 | 15 | 28 | |
| 50 | 49 | 75 | −26 | 55 | 60 | −5 | 69 | 32 | 37 | 87 | 14 | 73 | |
| 25 | 67 | 71 | −4 | 74 | 56 | 18 | 94 | 30 | 64 | 118 | 13 | 105 | |
| 0 | 78 | 65 | 13 | 87 | 51 | 36 | 110 | 28 | 82 | 138 | 12 | 126 | |
| −25 | 86 | 55 | 31 | 95 | 44 | 51 | 121 | 24 | 97 | 151 | 10 | 141 | |
| −50 | 91 | 41 | 50 | 101 | 32 | 69 | 128 | 17 | 111 | 160 | 7 | 153 | |
| −75 | 97 | 20 | 77 | 107 | 16 | 91 | 136 | 9 | 127 | 170 | 4 | 166 | |
| −100 | 100 | 0 | 100 | 112 | 0 | 112 | 142 | 0 | 142 | 177 | 0 | 177 | $8\times R_2$ |

torque curves in Fig. 5 are obtained. These test curves are shown in solid lines.

Finally, the torques at a given speed under the above unbalanced primary voltage conditions were calculated by taking the difference between the torques produced by the

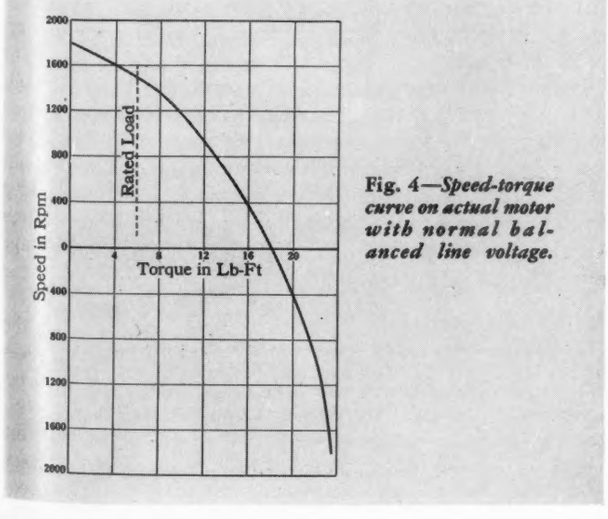



**Fig. 4—*Speed-torque curve on actual motor with normal balanced line voltage.***

TABLE IV—TEST DATA ON ACTUAL MOTOR WITH UNBALANCED PRIMARY VOLTAGE

| Speed in RPM | Torque in Lb-Ft | Current in Amps. | | | Motor Line Volts | | | |
|---|---|---|---|---|---|---|---|---|
| | | $I_3$ | $I_2$ | $I_1$ | $T_1-T_2$ | $T_2-T_3$ | $T_1-T_3$ | |
| 1800 | −6.75 | 15.8 | 15.3 | 10.5 | 41 | 242 | 222 | |
| 1220 | −2.25 | 18.5 | 11.7 | 10.3 | | 242 | 222 | |
| 830 | 0 | 20.1 | 10.9 | 9.9 | 40.5 | 242 | 222 | |
| 490 | 1.31 | 21.5 | 11.6 | 9.75 | 40 | 242 | 222 | |
| 400 | 1.35 | 21.1 | 11.6 | 9.5 | 40 | 242 | 222 | |
| 265 | 1.8 | 21.3 | 12.3 | 9.45 | 40 | 242 | 222 | |
| 0 | 3.45 | 21.7 | 12.6 | 9.3 | 40 | 242 | 222 | |
| −400 | 4.95 | 22.5 | 14.0 | 10.2 | 40 | 242 | 222 | |
| −1000 | 6.75 | 21.5 | 15.2 | 12.2 | 40 | 242 | 222 | |
| −1800 | 10.5 | 20.0 | 17.7 | 15.2 | 39 | 242 | 222 | $T_1$ on 220 V Tap |
| 1800 | −3.38 | 11.1 | 11.2 | 6.15 | 103 | 242 | 200 | |
| 1475 | 0 | 13.2 | 9.75 | 5.75 | 102 | 242 | 200 | |
| 1340 | 1.12 | 14.3 | 9.5 | 5.75 | 102 | 242 | 200 | |
| 670 | 4.95 | 18.2 | 11.6 | 6.75 | 102 | 242 | 202 | |
| 0 | 7.9 | 20.7 | 15.0 | 9.0 | 101 | 242 | 200 | |
| −385 | 9.4 | 21.1 | 16.3 | 10.8 | 100 | 242 | 200 | |
| −1000 | 11.1 | 21.6 | 18.2 | 14.5 | 101 | 242 | 200 | |
| −1820 | 13.9 | 22.2 | 18.7 | 19.5 | 100 | 242 | 198 | $T_1$ on 160 V Tap |
| 1800 | −1.87 | 7.5 | 8.75 | 3.0 | 152 | 242 | 193 | |
| 1600 | 1.12 | 9.28 | 7.64 | 1.9 | 155 | 242 | 196 | |
| 980 | 6.75 | 14.4 | 10.8 | 4.75 | 151 | 242 | 194 | |
| 450 | 10.0 | 17.5 | 14.1 | 8.25 | 150 | 242 | 194 | |
| 0 | 11.6 | 19.5 | 17.0 | 11.2 | 152 | 242 | 194 | |
| −510 | 14.1 | 21.2 | 19.2 | 14.5 | 150 | 242 | 194 | |
| −1000 | 15.4 | 23.2 | 21.0 | 17.5 | 151 | 242 | 194 | |
| −1800 | 17.0 | 24.7 | 22.5 | 22.5 | 150 | 242 | 192 | $T_1$ on 110 V Tap |

TABLE V—CALCULATED TORQUES ON ACTUAL MOTOR WITH UNBALANCED PRIMARY VOLTAGE

| Speed in RPM | Torque in Lb. Ft. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $T_1$ on 220V Tap | | | $T_1$ on 160V Tap | | | $T_1$ on 110V Tap | | |
| | Pos. Seq. | Neg. Seq. | Res. | Pos. Seq. | Neg. Seq. | Res. | Pos. Seq. | Neg. Seq. | Res. |
| 1800 | 0 | 6.2 | −6.2 | 0 | 3.4 | −3.4 | 0 | 1.4 | −1.4 |
| 1400 | 3.4 | 6.1 | −2.7 | 4.3 | 3.3 | 1.0 | 5.6 | 1.4 | 4.2 |
| 1000 | 5.0 | 5.9 | −0.9 | 6.5 | 3.2 | 3.3 | 8.6 | 1.4 | 7.2 |
| 600 | 6.5 | 5.6 | 0.9 | 8.2 | 3.0 | 5.2 | 10.7 | 1.3 | 9.4 |
| 0 | 8.1 | 4.8 | 3.3 | 10.2 | 2.6 | 7.6 | 13.4 | 1.1 | 12.3 |
| −600 | 9.5 | 3.8 | 5.7 | 12.0 | 2.1 | 9.9 | 15.7 | 0.9 | 14.8 |
| −1000 | 10.0 | 3.0 | 7.0 | 12.6 | 1.6 | 11.0 | 16.6 | 0.7 | 15.9 |
| −1400 | 10.3 | 2.0 | 8.3 | 13.1 | 1.1 | 13.0 | 17.2 | 0.5 | 16.7 |
| −1800 | 10.6 | 0 | 10.6 | 13.3 | 0 | 13.3 | 17.5 | 0 | 17.5 |

positive- and negative-sequence voltages in the same manner as previously explained for the hypothetical motor. These results are listed in table V, and from this data the calculated speed-torque curves for the actual motor were drawn in dotted lines on Fig. 5.

Comparison of the test speed-torque curves on the actual motor with the calculated ones, all on Fig. 5, shows this method of calculating speed-torque curves under unbalanced primary voltage conditions is quite accurate.

## Practical Significance of Primary-Voltage Unbalancing

By providing varying amounts of unbalance in the primary voltage and selecting suitable values of external secondary resistance, speed-torque curves of almost any desired characteristics can be procured with a wound-rotor induction motor. These speed-torque curves can be varied to cover all four quadrants of the graph. Hence, as far as speed-torque characteristics only are concerned, many things that can be accomplished by a d-c motor and control can be equaled by an a-c motor and control.

However, this system has a disadvantage that limits the scope of its usefulness considerably. The unbalancing of the primary voltage on an a-c polyphase motor causes it to draw relatively large currents from the line. These currents are in the order of 150 to 300 per cent of the rated full-load current, the magnitude depending upon the amount of unbalance in

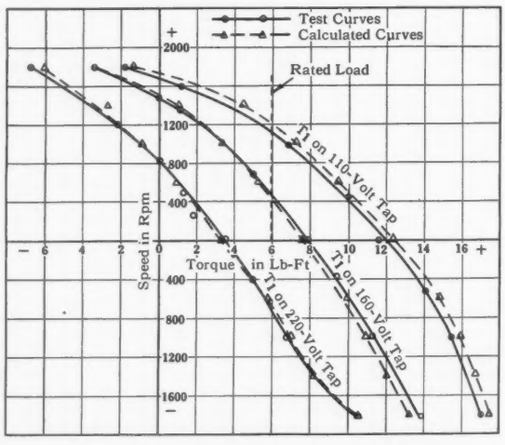



**Fig. 5—*Test and calculated speed-torque curves on actual motor with unbalanced primary voltage.***

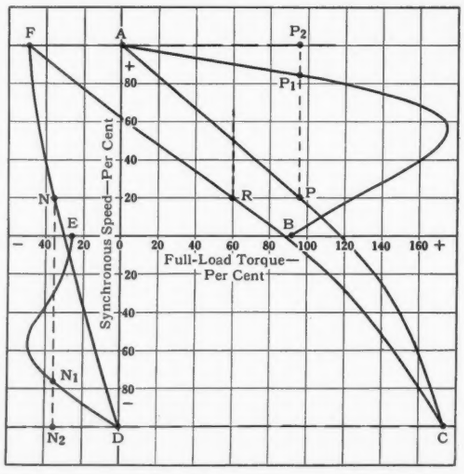



**Fig. 6—*A method of determining rotor loss under unbalanced primary-voltage conditions.***

the primary voltage. To illustrate this point of high primary current, refer to the test data in table IV. Using the middle set of data, $T_1$ on 160-volt tap, by interpolation, the current at full-load torque (6 pound-feet) output is 19.1 amperes in lead $T_3$, 12.8 amperes in lead $T_2$, and 7.55 amperes in lead $T_1$. This gives an rms value of 14 amperes, which is 233 per cent of the rated full-load current of 6 amperes.

The unbalanced primary voltage also causes increased losses in the rotor. Figure 6 shows how the rotor losses are affected. Curve $AB$ is a speed-torque curve of a hypothetical wound-rotor induction motor with the secondary short-circuited and at a reduced (balanced) voltage comparable to the positive-sequence voltage. Curve $AC$ shows the speed-torque characteristics of this motor under the same conditions as above, except with sufficient secondary resistance added to bring the pull-out torque down to $-100$ per cent synchronous speed. Curve $DE$ is the negative-sequence speed-torque curve with the secondary short circuited, and $DF$ with the optimum value of secondary resistance. $FC$ then is the resultant speed-torque curve of the motor with the unbalanced primary voltage that produced the positive- and negative-sequence voltages above. Assume this motor is to be operated under this particular condition of primary-voltage unbalance and secondary resistance at a torque equal to 60 per cent of rated full-load torque. Thus, as far as the motor output is concerned, operation is at point $R$ on curve $FC$, but insofar as the rotor losses in the motor itself are concerned, we are operating at point $P$ on the positive-sequence curve $AC$ and at point $N$ on the negative-sequence curve $DF$. The dotted line $PP_2$ is proportional to the total rotor loss for the positive sequence, of which $PP_1$ is dissipated in the external secondary resistance and $P_1P_2$ in the motor itself. Similarly, $NN_2$ is proportional to the total negative-sequence rotor loss, of which $NN_1$ is dissipated externally and $N_1N_2$ internally. The rotor copper loss is equal to the product of the slip and the torque produced at that slip. Hence, the actual total loss in the rotor of this hypothetical motor that will contribute to motor heating is

$$(0.16\times0.95)+(0.24\times0.35)=0.152+0.084=23.6 \text{ per cent.}$$

(The 16 per cent in the preceding equation is $P_1P_2$, and the 95 per cent is the torque there; the 24 per cent is $N_1N_2$, and the 35 per cent is the torque there.) If the normal slip of this motor when running at full load with the secondary short-circuited is 7.5 per cent, then the rotor heating will be increased by

$$\left(\frac{23.6}{7.5\times1.0}=3.15\right)$$

315 per cent when operating at 60 per cent load under this particular condition of primary-voltage unbalance and secondary resistance.

To obtain an overall picture of motor heating, assume that the total heating losses in the average motor under normal operating conditions can be divided as follows: 30 per cent in the primary copper, 40 per cent in the secondary copper, and 30 per cent in the iron. From the previous discussion, by reason of applying an unbalanced primary voltage, the primary copper losses (increasing as the square of the current) are about five times as great, or 150 per cent, and the secondary copper losses about three times as great, or 120 per cent. The iron loss will not change appreciably. Hence, the new total losses are $150+120+30=300$ per cent, and the motor heating is about three times as much as under normal full-load conditions.

If the motor operates with these excessive losses it will obviously overheat, thus hastening the deterioration of the insulation on the motor windings with consequent danger of motor failure. In conclusion, when employing this method of speed control, the actual duty cycle should be studied in detail to determine the effect on the motor, thus assuring the selection of a motor that will fulfill the requirements without exceeding a safe temperature rise.

## Turning a Vice Into a Virtue

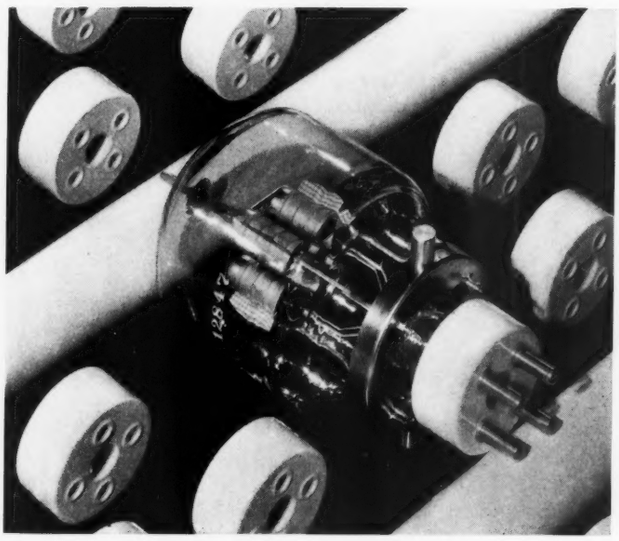
Unbalance in voltage supplied to a polyphase induction motor has long been looked upon as something to be avoided. The ills that result were discussed long ago in engineering literature*. But, just as nothing is completely bad, the reduced speeds possible with controlled voltage unbalance, as described above, may for some induction-motor applications be a useful attribute that outweighs the various undesirable effects.

*"Effect of Unbalanced Voltages on the Operation of Induction Motors," by O. C. Schoenfeld, *The Electric Journal*, Jan., 1925, p. 30.

# What's New!

## Tube Bases of Prestite

A GENERATION ago, electron effect was a scientist's curiosity. Today, electronic tubes are the heart of countless devices, a heart that beats at selected rates from a cycle every few minutes to some 30 billion cycles a second. Successful war cannot be waged without these "bottles." Yet component materials are scarce and getting scarcer. Tube bases, formerly made of now critical plastic materials, are a high priority hurdle for manufacturers to clear. It is, therefore, easy to see the importance of the application of Prestite, a ceramic made in this country from non-critical domestic materials, to electronic tube-base use.



*Precision made, of non-critical materials, these Prestite tube bases are serving daily in many military and industrial electronic equipments.*

Prestite, combining the electrical and mechanical strength of wet-process porcelain with the molding qualities of dry-process porcelain, is formed under tremendous hydraulic pressure, which imparts a dense grain structure. Unlike ordinary porcelains, Prestite can be held close to specified dimensions. Its forming ability makes it an easy material to produce in the desired shape for use in bases for power tubes. Bases made of Prestite possess the mechanical and electrical characteristics to meet all normal performance specifications. Tests show that it has a high dielectric strength and a loss factor better than that required in specifications for standard power tubes. Use of this alternate, non-critical material has enabled the tube manufacturer to meet delivery schedules without loss of time.

## Laminated Plastic Ball-Bearing Retainer Ring

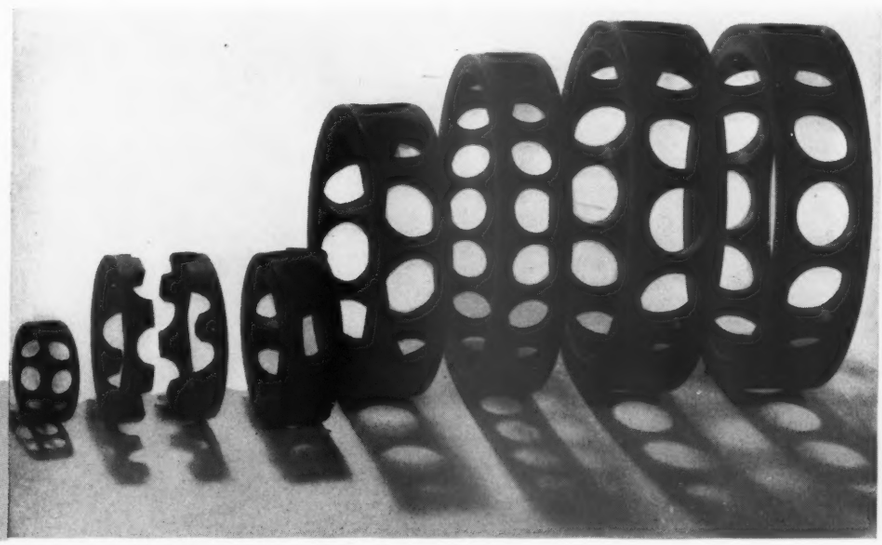
UNDER the pressure of high-speed, continuous operation such as is mandatory these days, details of construction have an important influence upon performance, as in ball bearings. The retainers in fairly precise bearings have been stamped from their sheet-steel; more heavily loaded and precise bearings have machined bronze retainers. For speeds of about 60 000 rpm and tolerances in one grinding operation of half a ten-thousandth of an inch, something new had to be added. Machining the retainer from Micarta increases permissible speed, increases life, and permits heavier loading of bearing with greater precision in spindle truth.

It was formerly thought that the design of the retainer was of secondary import. In comparison to the tolerance of five one-millionths of an inch to which the balls were held, the construction of the retainer was almost casual. However, the retainer design has been the subject of considerable research and it was found to have a vital influence on performance, particularly at high speeds. The ideal retainer must be strong yet light, inexpensive but accurate dimensionally, rigid but resistant to fatigue.

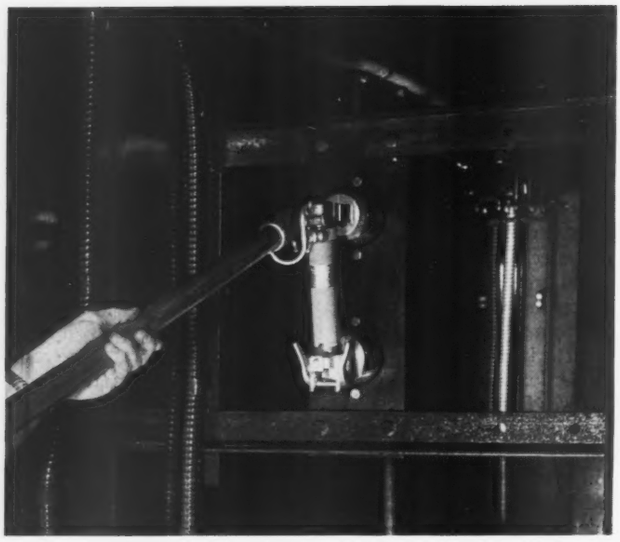
Retainers made of Micarta have these attributes. They are light but have great mechanical strength. Machined accurately in automatic machines, they are produced economically of materials less critical than steel or bronze. The rigidity of the ring is good, but being of plastic, it has a greater shock-absorbing power and is less subject to vibration and fatigue. With plastic retainers, the bearing operates quieter. One additional factor of great importance is the better lubrication of the bearing where Micarta retainers are used. This is because the laminated plastic *wets* better, making for better adherence to the lubricant.

The operating experience of Micarta retainers is dramatic in its demonstration of increased bearing efficiency. One bearing in a high-speed grinder, after over 18 billion revolutions, was examined and reinstalled in the machine as satisfactory for continued precision operation. Another high-speed grinder, after 15 months' operation of the same bearings with Micarta retainers, still turned out work with a tolerance of half a ten-thousandth of an inch. These retainers also permitted the increase in spindle speed that upped production from 17 to 65 pieces an hour.

These retainers of cloth-laminated plastic are lighter than metal, quieter, and permit faster machine operation with less friction at the bearing. They are made in automatic tool machines to close tolerances in a range of sizes from $\frac{3}{8}$ inch in diameter, the smallest, to nine inches in diameter, the largest.



*Applicable to most ball-bearing designs, these Micarta retainer rings are strong, dimensionally accurate, and rigid. Yet they are light and not responsive to vibration and quite resistant to fatigue.*



*Though small, this type* BAL *current-limiting fuse installed in an outdoor switchhouse will interrupt a 60 000-ampere circuit at 2.5 kv.*

## Type BAL Current-Limiting Power Fuse

The new three-element type BAL current-limiting potential transformer fuse announced several years ago has recently been extended into the power-fuse field. This broadened field provides short-circuit protection for high-voltage motor starters, small loads, and apparatus connected to electrical systems capable of delivering high short-circuit currents. A parallel development has provided a line of motor starters coordinated with the current-limiting ability of the BAL fuse.

The heart of the new fuse is the current-limiting element. The conducting portion is a plurality of specially rolled silver wires. These large-size wires are constricted at regular intervals so that they resemble a string of sausages. Parallel with this current-limiting element is a voltage-limiting resistor element consisting of two resistor wires wrapped in opposite directions to minimize the inductive effect. A third element is the series "clean-up" fuse incorporating boric acid for extinguishing the arc. Coarse silica sand in the current-limiting chamber condenses the metal vapors from the fusible elements and cools the fibre gases, thus eliminating high pressures within the fuse.

The magnitude of the fault current determines which of two ways the fuse shall operate. On a current of overload magnitude, the series fuse operates in the same manner as a conventional boric-acid power fuse. Under this condition, the current-limiting element does not fuse and plays no part in the interruption.

On short-circuit currents where the series fuse element melts in a small fraction of a cycle, the current-limiting element melts almost simultaneously. The fusion of the current-limiting elements and the action of the resulting arcs in the restricting fiber slots tend to produce an arc voltage sufficient to prevent further increase in the fault current and transfer the current immediately to the shunt resistor.

The resistor in parallel with the current-limiting element maintains low voltage during interruption, since the maximum voltage that can appear is the IR drop through the resistor. The series fuse arcs throughout the current-limiting action and interrupts the resistor current at the first current zero. As this current is resistance limited, it is easily interrupted.

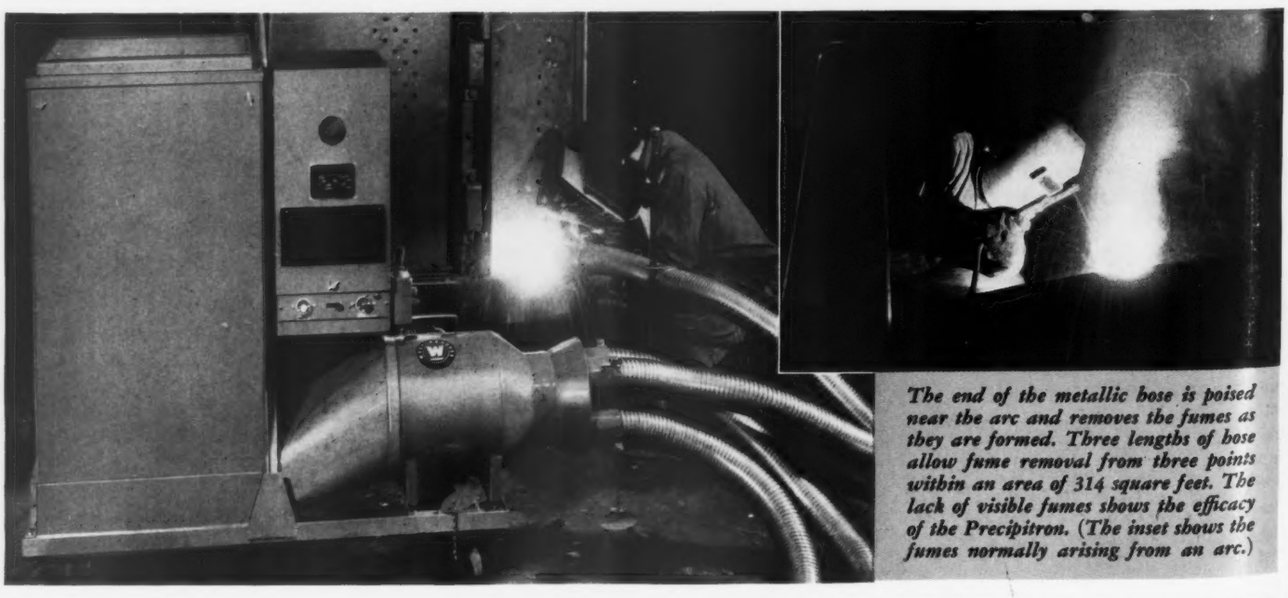
This combination of the new current-limiting element, a non-inductive resistor, and boric-acid series fuse is incorporated in a more compactly constructed fuse than has heretofore been available. The new fuse is suitable for application on distribution systems to interrupt the full range of fault currents, within its rating, with minimum system disturbance.

## Fumes Removed Electrically

THE familiar picture of a welder, highlighted by the wavering glare of the arc and beclouded by the rising welding fumes, has been altered. The fumes are being removed from the picture. Long regarded a concomitant part of industrial welding, the haze caused by welding fumes has been an expense and an annoyance. A new application of the Precipitron, the electrostatic air cleaner, eliminates the annoyance and expense by precipitating the minute solid particles that comprise the welding smokes and fumes.

A new, portable packaged unit that has been so successful in combating oil mist and smokes from high-speed machine tools, is now fitted with three metal hose for removal of welding fumes and smoke from one, two, or three separate arc-welding operations. This is a standard 600-cubic-feet-per-minute unit mounted on casters. It also has a steel eye to permit crane pickup for transfer to a distant part of the plant.

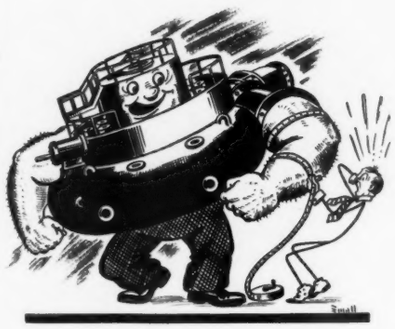
The Precipitron removes from the air more than 90 per cent of all air-borne particles, even those measuring but one two-hundred-fifty-thousandth of an inch—the smallest size particles comprising welding smoke. Thus, more than 90 per cent of the particles comprising welding fumes and smoke are removed.



*The end of the metallic hose is poised near the arc and removes the fumes as they are formed. Three lengths of hose allow fume removal from three points within an area of 314 square feet. The lack of visible fumes shows the efficacy of the Precipitron. (The inset shows the fumes normally arising from an arc.)*

# PERSONALITY PROFILES

*Harold I. Howell* has been diligently engaged in possibly the world's oldest branch of organized engineering—making water do man's bidding. Upon leaving the University of Michigan in 1923 with a bachelor's degree in civil engineering, he assisted with the construction of harbor improvements at Green Bay, Wisconsin; then, as field engineer, he had a hand in the construction of the hydroelectric project on the Clarion River in Pennsylvania.



This was followed by a period of experience at Daytona, Florida, on improvement of waterworks and sewage systems. With this background he entered the engineering department of the Niagara Falls Power Company, which system has a not inconsiderable number of hydroelectric plants—a total of 88. In this capacity he assisted with the design and construction of steam and hydroelectric plants, transmission lines, etc. Since 1936 he has been assistant to Dr. Norman R. Gibson, Vice-President and Chief Engineer of the Niagara Hudson System, who originated the method of testing hydraulic turbines Howell discusses in this issue. In 1934 he went to Russia to instruct the engineers in the application of the Gibson method to the machines in what was the Dnieper River plant before it became a war victim. Howell does his relaxing at the Zoar Valley Hunt Club, near Buffalo—an organization having nothing to do with hydraulic activities and very little with hunting.

* * *

Many roads lead to Westinghouse, and it is commonplace for authors whose silhouettes appear here to come from little-known communities or from far-flung universities. In *R. F. Woll*, a new note is sounded—home pastures look green to him. A native-born Pittsburgher, he came to Westinghouse upon graduation from the University of Pittsburgh in 1937 with the degree of B.S. in electrical engineering. Woll started on the motor-test floor, and in 1939 was transferred to the engineering department. In addition to designing industrial motors, he taught war-training classes at University of Pittsburgh night school.

* * *

A trio of repeat performers appear as authors in this issue. *M. A. Hyde* and *W. G. James* last appeared in the August 1942 issue, and *R. E. Marbury* in November 1943. Once again M. A. Hyde writes of matters connected with the operation of a large petroleum pipe line, in particular, an electrical problem. The solution for this one involved the use of capacitors, which are the peculiar province of R. E. Marbury—so the collaboration of the two on the article was a natural. Hyde has been doing engineering work in connection with the electrification of refineries, etc., since 1925 and Marbury has been active in the capacitor field since 1918.

When W. G. James writes of the problems and development of high-voltage bushings, he draws upon first-hand experience with the designing of 65 000-kva transformers used on a 287-kv line.

* * *

Twenty-one years' experience has made *H. J. Lingal* an authority in matters of circuit breakers, their auxiliaries, and various protective devices—but particularly large oil circuit breakers and their bushings. And he has achieved this position without the aid of a formal technical education. He joined the Westinghouse Company in 1923, entering immediately the Switchgear Division where, in the course of the years, he has been associated with the entire gamut of circuit breakers from the lowest voltage to the highest. He had much to do with the bushings for the Boulder Dam 287-kv circuit breakers. In helping bring the high-voltage condenser bushing to its present status he has been closely associated with work done in the high-voltage impulse laboratory. The occasions he has served on various engineering association committees for the development of apparatus and insulation standards are too numerous to count.

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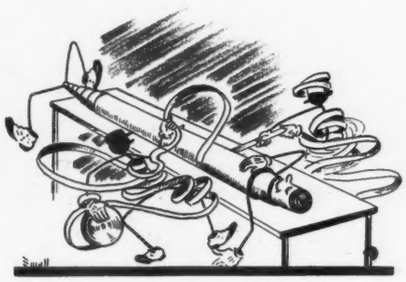
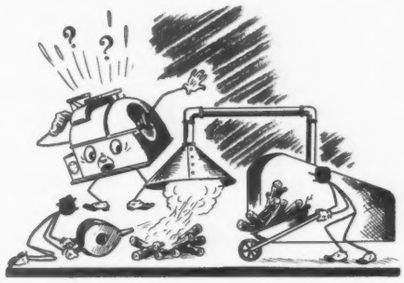


To many, the differences between the several branches of engineering stand as a barrier that would prevent facile movement from one field to the other. But not to *F. K. Fischer*. He studied electrical engineering at Rensselaer Polytechnic Institute, obtaining his degree in 1930. He joined Westinghouse the same year, attending its graduate school, specializing in mechanics. After a turn of about a year each in the Circuit Breaker and Motor Engineering Departments he became a member of the Experimental Engineering Department of the Steam Apparatus Division. For five years, beginning in 1934, he was a designer of steam condensers. Now, as a steam-application engineer, he journeys over a wide area in the East assisting central-station and industrial engineers to solve steam problems. He has done considerable engineering writing and has taught many courses in steam and mechanical engineering.



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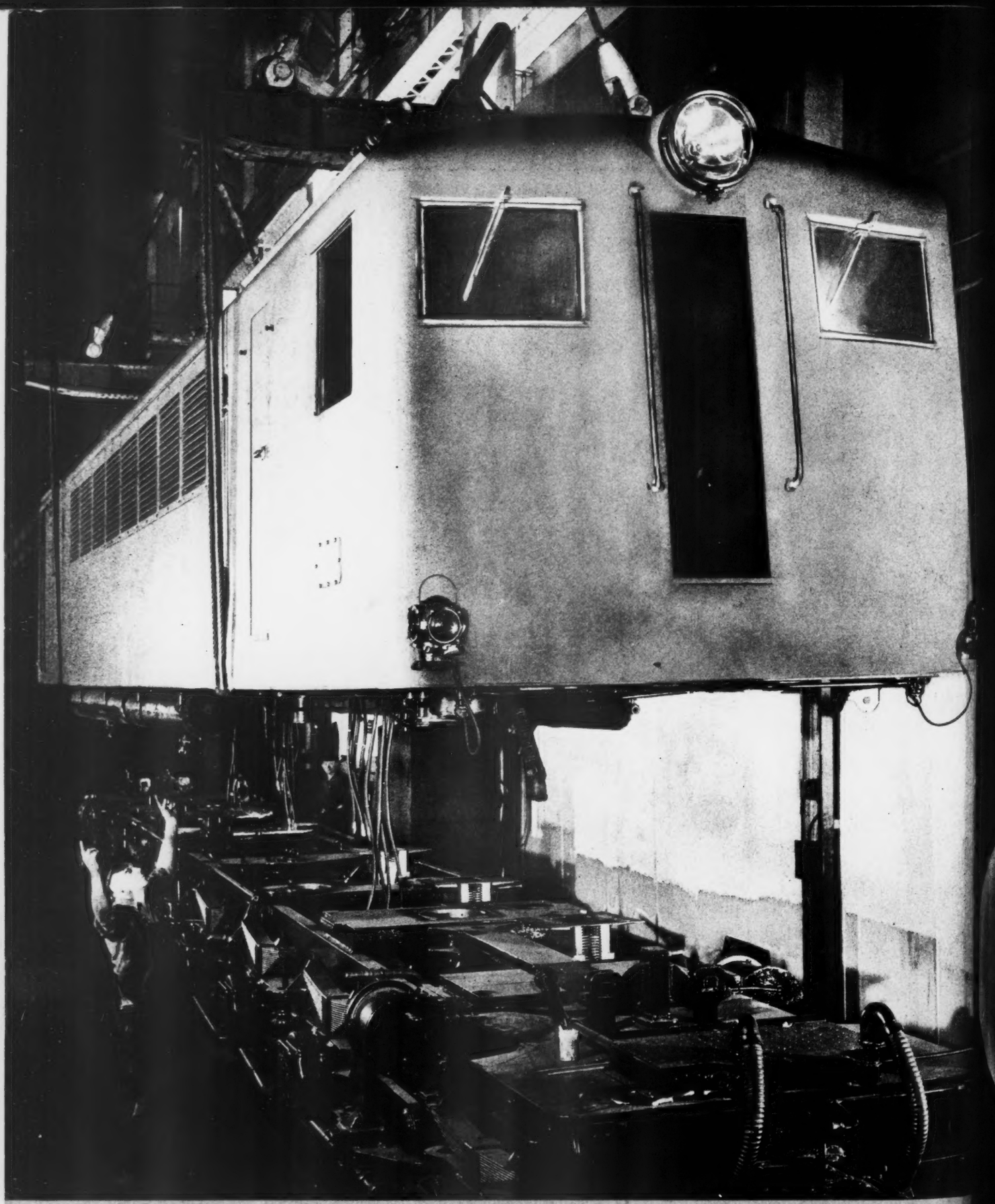
The old saw about prophets and honor does not apply in the case of *Charles A. Meyer*. He commands respect "in his own country" as a top-flight expert in thermodynamics, and his reputation in this field has already spread beyond the Westinghouse Company to a wide circle of mechanical engineering. Since coming to Westinghouse in 1933, having just been graduated from Villanova with a B.S. degree in mechanical engineering, he has been associated with engine and turbine research. In this he has accumulated experience with internal-combustion engines, blowers, blade efficiencies of steam turbines, valves, losses in labyrinths, and vibration and dampening. Since the beginning of this year Meyer has been head of the section on thermodynamics, in which group analyses are made of the thermal performance of the components of gas turbines. He has done a great deal of lecturing to local engineering groups on thermodynamics, mathematics, and fluid flow. When we asked him what he would do if he had some spare time, he replied, "I'd faint."



## MORE POWER TO BRAZIL

*Steam locomotives of the Sorocabana Railway in Brazil that formerly burned imported coal and a great deal of domestic wood, are being replaced by 1940-horsepower electric locomotives such as this. One of ten similar units under construction, this meter-gauge locomotive will draw a twelve-car train at 60 mph.*